

## **Chapter 4**

# **Competitiveness**

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This chapter of the Cleaner Technologies Substitutes Assessment (CTSA) presents information on basic issues traditionally important to the competitiveness of a printed wiring board (PWB) manufacturer: the performance characteristics of the making holes conductive (MHC) technologies relative to industry standards; the direct and indirect production costs associated with the MHC technologies; the federal environmental regulations affecting chemicals used in or waste streams generated by a technology; and the implications of an MHC technology choice on global competitiveness. A CTSA weighs these traditional competitiveness issues against issues business leaders now know are equally important: the health and environmental impacts of alternative products, processes, and technologies. Section 4.1 presents the results of the Performance Demonstration Project. Section 4.2 presents a comparative cost analysis of the MHC technologies. Section 4.3 lists the federal environmental regulations affecting chemicals in the various technologies. Section 4.4 summarizes information pertaining to the international use of the technologies, including reasons for adopting alternatives to electroless copper worldwide.

### **4.1 PERFORMANCE DEMONSTRATION RESULTS**

#### **4.1.1 Background**

This section of the CTSA summarizes performance information collected during performance demonstrations of MHC technologies. These demonstrations were conducted at 25 volunteer PWB facilities in the U.S. and Europe, between September and November, 1995. Information from the performance demonstrations, taken in conjunction with risk, cost, and other information in this document, provides a more complete assessment of alternative technologies than has previously been available from one source.

In a joint and collaborative effort, Design for the Environment (DfE) project partners organized and conducted the performance demonstrations. The demonstrations were open to all suppliers of MHC technologies. Prior to the start of the demonstrations, DfE project partners advertised the project and requested participation from all interested suppliers through trade shows, conferences, trade journals, and direct telephone calls.

#### **4.1.2 Performance Demonstration Methodology**

The detailed performance demonstration methodology is attached in Appendix F. The general plan for the demonstrations was to collect information about MHC technologies at facilities where the technologies were already in use. The information collected through the demonstrations was intended to provide a “snapshot” of the way the technology was performing at that particular facility at that particular time. It is important to note that the methodology was developed by consensus by a technical workgroup, which included suppliers, trade association representatives, the U.S. Environmental Protection Agency (EPA), and many PWB manufacturers.

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Each supplier was asked to submit the names of up to two facilities where they wanted to see the demonstrations of their technology conducted. This selection process encouraged the suppliers to nominate the facilities where their technology was performing at its best. This, in turn, provided for more consistent comparisons across technologies. The sites included 23 production facilities and two supplier testing facilities. While there were no pre-screening requirements for the technologies, the demonstration facilities did have to meet the requirements of the performance demonstration methodology.

For the purposes of the Performance Demonstration Project, the MHC process was defined as everything from the desmear step through 0.1 mil of copper flash plating. In order to minimize differences in performance due to processes outside this defined MHC function, the panels used for testing were all manufactured and drilled at one facility. One hundred panels, described below, were produced. After drilling, three panels were sealed in plastic bags with desiccant and shipped to each test site to be processed through the site's MHC line. All bags containing panels remained sealed until the day of processing.

An on-site observer from the DfE project team was present at each site from the point the bags were opened until processing of the test panels was completed. Observers were present to confirm that all processing was completed according to the methodology and to record data. Each test site's process was completed within one day; MHC processing at all sites was completed over a two month period.

When the MHC processing was completed, the panels were put into sealed bags with desiccant and shipped to a single facility, where they remained until all the panels were collected. At this facility, the panels were electroplated with 1.0 mil of copper followed by a tin-lead etch resist, etched, stripped of tin-lead, solder mask coated, and finished with hot air solder leveling (HASL). A detailed account of the steps taken in this process is included in Appendix F.

After HASL, the microsection coupons were routed out of the panels and sent to Robisan Laboratory Inc. for mechanical testing. The Interconnect Stress Test (IST) coupons were left in panel format. The panels containing the coupons were passed twice through an IR reflow to simulate assembly stress. A detailed protocol describing the IR reflow process is also included in Appendix F. The panels with the IST coupons were then sent to Digital Equipment Corporation of Canada (DEC Canada) for electrical prescreening and electrical testing.

### **Limitations of Performance Demonstration Methodology**

This performance demonstration was designed to provide a snapshot of the performance of different MHC technologies. Because the test sites were not chosen randomly, the sample may not be representative of all PWB manufacturing facilities in the U.S. (although there is no specific reason to believe that they are not representative). In addition, the number of test sites for each type of technology ranged from one to ten. Due to the smaller number of test sites for some technologies, results for these technologies could more easily be due to chance than the results from technologies with more test sites. Statistical relevance cannot be determined.

### **4.1.3 Test Vehicle Design**

All of the test panels were manufactured by H-R Industries, Inc. The test panel measured 24" x 18", laminated to 0.062", with eight layers. Test panels were produced from B and C stage FR4 materials. Artwork, lamination specifications, and a list of the steps taken to manufacture the panels are included in Appendix F.

Each test panel contained 54 test coupons: 27 IST coupons (used for electrical testing) and 27 microsection coupons. IST coupons measured 6.5" x 3/4" and contained 700 interconnecting vias on a seven row by 100 via 0.050" grid. This coupon contained two independent circuits: the post circuit and the plated through-hole (PTH) circuit. The post circuit contained 200 interconnects, and was used to measure post interconnect resistance degradation. The PTH circuit contained 500 interconnects, and was used to measure PTH (barrel) interconnect resistance degradation. IST coupons had either 0.013" or 0.018" holes (finished).

The microsection coupon measured 2" x 2" and contained 100 interconnected vias on a 10 row by 10 via 0.100" grid. It had internal pads at the second and seventh layer and a daisy chain interconnect between the two surfaces of the coupon through the via. Microsection coupons had either 0.013", 0.018", or 0.036" holes (finished).

This study was a snapshot based on products built with B and C stage FR4 materials and this specific board construction. The data cannot necessarily be extrapolated to other board materials or constructions.

### **4.1.4 Electrical and Microsection Testing Methodology**

#### **Electrical Testing Methodology**

The IST coupons in panel format were electrically prescreened to determine defects on arrival. The panels were then shipped to another facility for routing of the IST coupons, and were shipped back to DEC Canada for completion of electrical testing.

Electrical testing was completed using the IST technology. IST is an accelerated stress test method used for evaluating the failure modes of PWB interconnect. This method uses DC current to create the required temperatures within the interconnect. There are three principal types of information generated from the IST:

- Initial resistance variability.
- Cycles to failure (barrel integrity).
- Post separation/degradation (post interconnect).

The resistance value for the first internal circuit (PTH circuit) for each coupon was determined. This gives an indication of the resistance variability (plating thickness) between coupons and between panels. The initial resistance testing was also used to determine which coupons had defects on arrival, or were unsuitable for further testing.

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The cycles to failure indicate how much stress the individual coupons can withstand before failing to function (measuring barrel integrity). IST coupons contained a second internal circuit (post circuit) used to monitor the resistance degradation of the post interconnect.

The level of electrical degradation in conjunction with the number of cycles completed is used to determine the presence and level of post separation. The relative performance of the internal circuits indicates which of the two internal circuits, the post circuit or the PTH circuit, has the dominant failure mechanism. The draft Institute for Interconnecting and Packaging Electronic Circuits (IPC) IST test method is included in Appendix F.

### **Mechanical Testing Methodology**

The coupons for mechanical testing were sent to Robisan Laboratory Inc. for testing. Mechanical testing consisted of evaluations of metallurgical microsections of plated through-holes in the “as produced” condition and after thermal stress. One test coupon of each hole size from each panel was sectioned. The direction the coupons were microsectioned was determined by visually examining the coupons to determine the direction of best registration to produce the most inner layer circuitry connections in the microsections.

Microsections were stressed per IPC-TM-650, method 2.6.8, included in Appendix F. The plated through-holes were evaluated for compliance to the requirements found in IPC-RB-276. Microsections were examined after final polish, prior to metallurgical microetch, and after microetch.

The original test plan called for selection of IST and microsectioning coupons from similar locations on each panel. Following prescreening, the coupon selection criteria was amended to be based on coupons with the best registration. This resulted in some coupons being selected from areas with known thicker copper (see Results of Electrical Prescreening below).

Four 0.013" IST coupons were selected from each of the three test panels from each test site. Test Site #3 and Test Site #4 had only two available test panels, therefore six coupons were selected from each panel. Three coupons from within six inches of the IST coupons selected were microsectioned from the same panels. In some cases, the desired microsection coupons exhibited misregistration, so next-best locations were used. In all cases, coupons selected were located as close to the center of the panel as possible.

### **Limitations of Testing Methodology**

Fine line evaluations in microsections have always been a point of contention within the industry. Current microsection specifications state that any indication of separation between the hole wall plating and the inner layer is sufficient grounds to reject the product. An indication of post separation would be a line on the microsection thicker than what normally appears with electroless copper technology (normal average: 0.02 - 0.04 mils). Separation may also be determined by a variation in the thickness of the line across the inner layer connection, especially on electroless deposits that are very thin. The rationale for these rejection criteria is that product with post separation degrades with time and temperature cycling.

With traditional electroless copper products where post separation is present, it can usually be determined where the separation occurs: between the electroless and foil, within the electroless, or between the electroless and the electrolytic plating. This determination often helps in troubleshooting the plating process. In this study, some of the alternative technologies resulted in no line at all after microetch on the microsections. This posed a problem in interpretation of results. If traditional criteria are used to determine inner layer separation (i.e., the line of demarcation is thicker on some inner connects than others, and the electroless can be seen as continuous between the inner layer and plated copper), then accurate evaluations of product with no lines would not be possible. In this study, the criteria used on “no line” products was that if the sections exhibited any line of demarcation after microetch, the product is considered to have inner layer separation.

This issue is significant to the PWB industry because there remains a question about the relationship between the appearance of a line on the microsection to the performance of a board. Traditionally (with electroless copper products), the appearance of a line thicker than normal electroless line is considered to be post separation, and the board is scrapped. However, there are no criteria for how to evaluate “no line” products. In addition, there are no official means of determining when “a little separation” is significant to the performance of the board.

IST is not a subjective test and is not dependent upon the presence or absence of a line in a microsection after microetch. The test provides a relative number of IST cycles necessary to cause a significant rise in resistance in the post interconnect. This number of cycles may be used to predict interconnect performance. Tests such as this, when correlated with microsections, can be useful in determining how to interpret “no line” product characteristics. In addition, IST may be able to determine levels of post separation.

The figures included in Appendix F in the IPC IST test method show various failure mechanisms exhibited by different test sites and panels. Future industry studies must determine the relevance of these curves to performance, based on number of cycles needed to raise the resistance as well as the amount of change in resistance. Definitions for “marginal” and “gross” separations may be tied to life-cycle testing and subsequently related to class of boards produced.

#### **4.1.5 Results**

Product performance for this study was divided into two functions: PTH cycles to failure and the integrity of the bond between the internal lands (post) and the PTH. The PTH cycles to failure observed in this study is a function of both electrolytic plating and the MHC process. The results indicate that each MHC technology has the capability to achieve comparable (or superior) levels of performance to electroless copper.

Results are presented in this section for all three stages of testing conducted:

1. Electrical prescreening, which included tests for:
  - Defects on arrival based on resistance measurements.
  - Print and etch variability based on resistance distribution of the post circuit.
  - Plating variability based on resistance distribution of the PTH circuit.

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2. Microsection evaluation, which examined:
  - Plating voids.
  - Drill smear.
  - Resin recession.
  - Post separation.
  - Average copper plating thickness.
3. Interconnect stress testing, which measured:
  - Mean cycles to failure of the PTH interconnect.
  - Post degradation/separation within the post interconnect.

### **Results of Electrical Prescreening**

Seventy-four of 75 test panels from 25 test facilities were returned. One of the 74 proved to be untestable due to missing inner layers. The results of the prescreening will be reported in the following categories: defects on arrival (unacceptable for testing), print and etch variability, and plating (thickness) variability.

**Defects on Arrival.** A total of 1,971 coupons from the 73 panels each received two resistance measurements using a four wire resistance meter. The total number of holes tested was 1.4 million. As shown in Table 4.1, one percent (19) of coupons were found to be defective, and were considered unacceptable for IST testing because of opens and shorts.

**Table 4.1 Defective Coupons Found at Prescreening**

Test Site #	MHC Technology	Opens	Shorts
1	Electroless		4
3	Electroless	1	2
11	Graphite	2	
12	Graphite		5
14	Palladium	1	
16	Palladium	2	
20	Palladium	2	

Following an inspection of the defective coupons, the opens were found to be caused by voiding, usually within a single via. Shorts were caused by misregistration. The type of MHC technology did not contribute to the shorts.

**Print and Etch Variability.** The resistance distribution for the post circuit was determined. Throughout manufacturing, the layers/panels were processed in the same orientation, which provided an opportunity to measure resistance distributions for each coupon/panel. The distribution proved very consistent. This result confirms that inner layer printing and etching did not contribute to overall resistance variability. Table 4.2 depicts the mean post circuit resistance for five 0.013" coupon locations (in milliohms) for all 73 panels.

**Table 4.2 Mean Post Circuit Resistance Measurements, in Milliohms  
(coupon locations on panel)**

409		405
	399	
415		411

**Plating Variability.** The resistance distribution for the PTH circuit was determined as an indicator of variability. The results indicated that overall resistance variability was due to plating thickness variability rather than print and etch variability. Table 4.3 depicts the mean PTH circuit resistance for five 0.013" coupon locations (in milliohms) for all 73 panels.

**Table 4.3 Mean PTH Circuit Resistance Measurements, in Milliohms  
(coupon locations on panel)**

254		239
	244	
241		225

The PTH interconnect resistance distribution showed the electrolytic copper plating increased in thickness from the top to the bottom of each panel. Copper thickness variability was calculated to be 0.0003" thicker at the bottom compared to the top of each panel. Resistance variability, based on 54 measurements per panel, was also found from right to left on the panels. Inconsistent drill registration or outer layer etching was thought to be the most probable cause of this variability. When a number of holes break out of their pads, it increases the internal copper area, causing the resistance to decrease. This reduction in resistance creates the impression the coupons have thicker copper.

Table 4.4 lists the means and standard deviation of all PTH resistance measurements and the levels of correlation among panels observed at each site. As seen in Table 4.4, copper plating distribution at each site was good. Plating cells and rack/panel locations did not create large variability that could affect the results of each test site. Because resistance (plating thickness) distribution was also consistent among test sites, relative comparisons among the different MHC technology sites can be made. Only one site, Test Site #12, was calculated to have poor correlation between all three panels.

It was determined during correlation that the variations in hole wall plating thickness indicated by electrical prescreening were due to variations in the flash plate provided by each test site and not due to variations in electrolytic plating.

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**Table 4.4 Prescreening Results - 0.013" Vias for All Test Sites<sup>a</sup>**

Site #	Mean Res.	Std Dev.	Pnl #1	Pnl #2	Pnl #3	Corr.
1	239	14.5	234	245	237	All
2	252	17.6	269	251	234	2
3	238	12.5	227	248	N/A	All
4	232	11.2	224	239	N/A	All
5	236	12.1	239	241	229	2
6	266	15.7	255	275	266	2
7	253	14.2	240	259	259	All
8	230	11.6	221	228	241	2
9	243	10.6	247	247	235	2
10	248	13.0	256	242	247	All
11	226	19.0	216	221	241	2
12	240	23.0	254	235	231	None
13	231	16.0	243	235	215	2
14	247	26.8	256	227	258	All
15	243	11.1	236	244	248	2
16	239	15.9	232	243	241	All
17	240	12.8	247	243	231	All
18	245	9.7	245	249	240	All
19	226	10.2	223	232	223	2
20	229	10.2	219	238	229	2
21	250	13.3	258	243	249	2
22	256	8.8	256	261	250	All
23	253	12.5	257	257	244	All
24	239	12.0	241	232	246	All
25	224	13.9	210	232	231	All

<sup>a</sup> Site #6, an electroless copper site, may not have performed to its true capability on the day of the test. Due to a malfunction in the line, the electroless copper bath was controlled by manual lab analysis instead of by the usual single-channel controller.

Mean Res. - Mean resistance of all coupons on the three panels.

Std Dev. - Standard deviation for all coupons per test site.

Pnl # - Mean resistance for listed panel.

Corr. - Correlation Coefficient >.7 between each panel.

Sample size for each test site: 12.

Remaining test results will be reported for each type of MHC technology, represented by the following test sites shown in Table 4.5.



**Table 4.5 Correlation of MHC Technologies with Test Site Numbers**

Test Site #	MHC Technology	# of Test Sites
1 - 7	Electroless Copper	7
8 - 9	Carbon	2
10 - 12	Graphite	3
13 - 22	Palladium	10
23 - 24	Non-Formaldehyde Electroless Copper	2
25	Conductive Polymer	1

### **Results of Microsection Evaluation**

The only defects reported in this study were voids in hole wall copper, drill smear, resin recession, and inner layer separation. Average hole wall thickness was also reported for each panel. Defects present but not included as part of this report are registration, inner layer foil cracks, and cracks in flash plating at the knees of the holes. These defects were not included because they were not believed to be a function of the MHC technology. The inner layer foil cracks appear to be the result of the drilling operation and not a result of z-axis expansion or defective foil. None of the cracks in the flash plating extended into the electrolytic plate in the coupons as received or after thermal stress. Therefore, the integrity of the hole wall was not affected by these small cracks.

**Plating Voids.** There were no plating voids noted on any of the coupons evaluated. The electrolytic copper plating was continuous and very even with no indication of any voids.

**Drill Smear.** The panels exhibited significant amounts of nailheading. Since nailheading was present on all panels, it was determined that all test sites had received similar panels to process and therefore, comparisons were possible. The main concern with the presence of nailheading was that the amount of drill smear might be excessive compared to each test site's "normal" product. Drill smear negatively impacts inner layer connections to the plated hole wall if not removed.

**Resin Recession.** No samples failed current specification requirements for resin recession. There was, however, a significant difference in the amount of resin recession among test sites.

**Inner Layer Separation.** Different chemistries had different appearances after metallurgical microetch. Electroless copper microsections traditionally have a definite line of demarcation between foil copper and electrolytic copper after metallurgical microetch. This line also appeared in electroless copper samples in this study. The line is the width of the electroless deposit, and is very important in making a determination as to whether inner layers are separated from the plated hole wall. Many of the products tested in this study had no line of demarcation or lines which had little, if any, measurable width. For those MHC technologies that should not have a line after microetch, the determination as to whether inner layer separation was present on the samples was based on the presence of a line.

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Over half of the test sites supplied product which did not exhibit inner layer separations on as received or thermal stressed microsections. Some of the product exhibited inner layer separation in the as received samples which further degraded after thermal stress. Other test sites had product that showed very good interconnect as received and became separated as a result of thermal stress.

The separations ranged from complete, very wide separations to very fine lines which did not extend across the complete inner layer connection. No attempt was made to track these degrees of separation because current specification requirements dictate that any separation is grounds for rejection of the product.

Table 4.6 gives the percentage of panels from a test site that did or did not exhibit a defect. The data are not presented by hole size because only Test Site #11 had defects on only one size of hole. In all other test sites exhibiting defects, the defects were noted on all sizes of holes.

**Table 4.6 Proportion of Panels Exhibiting Defects**

Test Site #	Percentage of Panels Exhibiting Defect			Percentage of Panels Exhibiting Defect per Technology (average of all test sites)			MHC Technology
	Drill Smr	Res Rec	Post Sep	Drill Smr	Res Rec	Post Sep	
1	0	33	0	21	31.6	31.6	Electroless Copper
2	66	66	100				
3	0	0	0				
4	100	0	0				
5	0	0	0				
6	0	0	100				
7	0	100	0				
8	0	0	0	0	0	0	Carbon
9	0	0	0				
10	0	0	0	0	11	55.6	Graphite
11	0	33	66				
12	0	0	100				
13	0	33	0	3.3	26.5	43.3	Palladium
14	0	0	0				
15	0	0	33				
16	0	0	100				
17	33	33	33				
18	0	33	66				
19	0	100	0				
20	0	0	100				
21	0	0	100				
22	0	66	0				
23	0	0	100	0	0	50	Non-Formaldehyde Electroless Copper
24	0	0	0				
25	0	0	0	0	0	0	Conductive Polymer

Table 4.7 depicts the average measured copper plating thickness for all panels.

**Table 4.7 Microsection Copper Plating Thickness (in mils)**

Test Site	Panel # 1	Panel # 2	Panel # 3	Average Cu
1	1.4	1.1	1.2	1.24
2	0.95	1.1	1.3	1.11
3	1.3	1.1	N/A	1.2
4	1.3	1.2	N/A	1.25
5	1.2	1.3	1.3	1.24
6	1.1	1.1	1.1	1.1
7	1.5	1.1	1.1	1.2
8	1.3	1.3	1.2	1.3
9	1.2	1.4	1.3	1.3
10	1.0	1.1	1.3	1.14
11	1.5	1.5	1.1	1.4
12	1.3	1.3	1.3	1.3
13	1.2	1.3	1.3	1.3
14	1.2	1.1	1.2	1.2
15	1.1	1.1	1.2	1.13
16	1.1	1.2	1.3	1.2
17	1.2	1.3	1.4	1.3
18	1.1	N/A	1.5	1.3
19	1.5	1.3	1.3	1.4
20	1.6	1.4	1.3	1.4
21	1.1	1.2	1.2	1.14
22	1.2	1.1	1.1	1.13
23	1.4	1.1	1.2	1.24
24	1.3	1.2	1.2	1.23
25	1.4	1.7	1.4	1.5

### **Results of Interconnect Stress Testing**

Test results will be reported in various formats. Both tables and graphs will be used to describe IST cycles to failure for the PTH interconnect and post degradation/separation within the post interconnect. IST was completed on a total of 12 coupons from each test site.

**Mean Cycles to Failure Testing Results.** The mean cycles to failure for the PTH interconnect are established at the point when the coupon exceeds a ten percent increase in the initial elevated resistance. Mean IST cycles to failure and standard deviation by test site are shown in Table 4.8. Table 4.9 shows the mean IST cycles to failure and standard deviations by MHC technology.

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**Table 4.8 Mean IST Cycles to Failure, by Test Site**

Test Site # & MHC Technology Type	IST Cycles to Fail	Standard Deviation
1 Electroless Copper	346	91.5
2 Electroless Copper	338	77.8
3 Electroless Copper	323	104.8
4 Electroless Copper	384	70
5 Electroless Copper	314	50
6 Electroless Copper	246	107
7 Electroless Copper	334	93.4
8 Carbon	344	62.5
9 Carbon	362	80.3
10 Graphite	317	80
11 Graphite	416	73.4
12 Graphite	313	63
13 Palladium	439	55.2
14 Palladium	284	62.8
15 Palladium	337	75.3
16 Palladium	171	145.7
17 Palladium	370	122.9
18 Palladium	224	59.7
19 Palladium	467	38.4
20 Palladium	443	52.5
21 Palladium	267	40.5
22 Palladium	232	86.6
23 Non-Formaldehyde Electroless Copper	214	133.3
24 Non-Formaldehyde Electroless Copper	261	41.6
25 Conductive Polymer	289	63.1

Sample size = 12 coupons from each site.

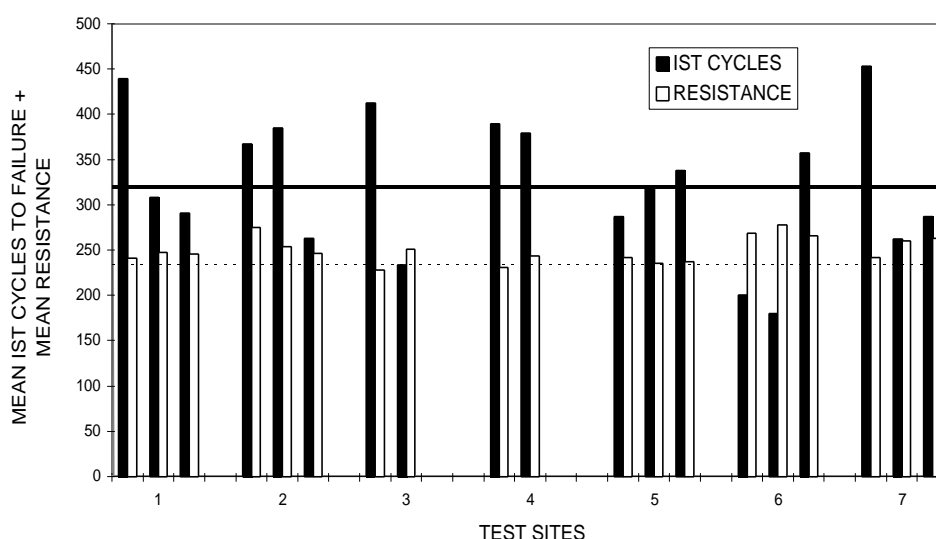
**Table 4.9 Mean IST Cycles to Failure, by MHC Technology**

MHC Technology	IST Cycles to Fail	Standard Deviation
Electroless Copper	327	92.5
Carbon	354	71
Conductive Polymer	289	63.1
Graphite	349	85.3
Non-Formaldehyde Electroless Copper	238	99.5
Palladium	332	126

High standard deviations indicate that high levels of performance variability exist within and among test sites.

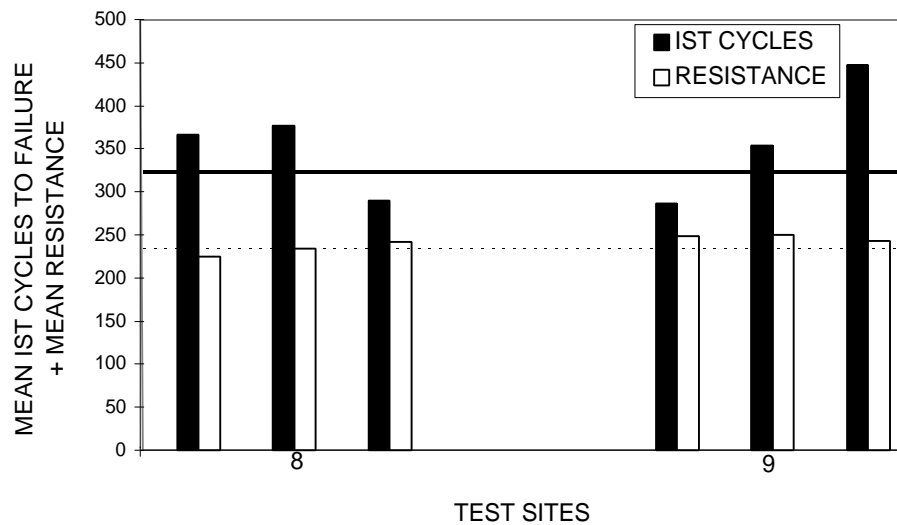
Figures 4.1 through 4.6 identify the IST cycles to failure for each panel and test site for each MHC technology. The two reference lines on each graph identify the mean cycles to failure (solid line) for all 300 coupons tested (324 cycles) and the mean resistance (dotted line) for all coupons measured (241 milliohms). When considering the overall performance of each panel, it is useful to compare the mean resistance of the coupons to the dotted reference line. As mentioned before, each test site was instructed to flash plate 0.0001" of electrolytic copper into the holes. If the sites exceeded this thickness, the total copper thickness would be thicker, lowering the resistance and increasing the performance of the panels. Therefore, panels with lower resistance should be expected to perform better, and vice versa. Although each site was requested to plate 0.0001" of electrolytic copper, the actual range was between 0.00005" and 0.0005".

**Figure 4.1 Electroless Copper - IST Cycles to Fail vs. Resistance**



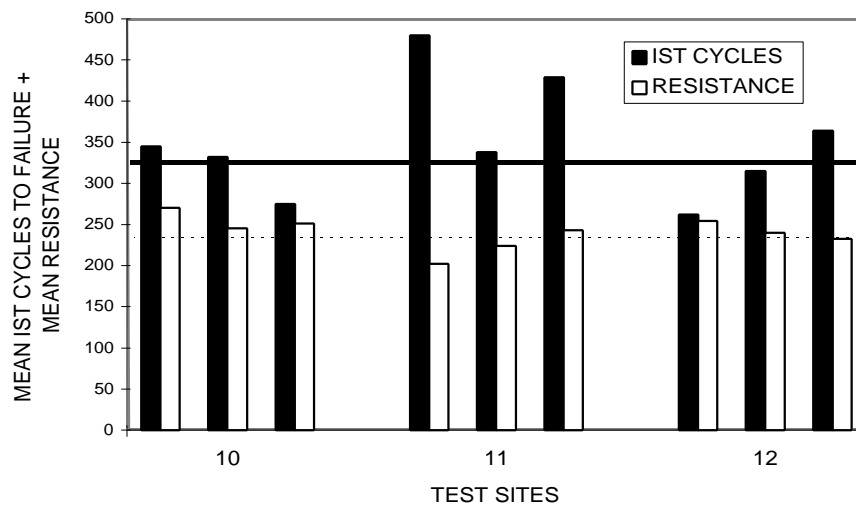
All electroless copper test sites had at least one panel that met or exceeded the mean performance. As shown in Figure 4.1, for the panels that did not achieve the mean performance, it can be seen that the mean resistance column was above the reference line (thinner copper). The exception was Test Site #6, which exhibited a high degree of post separation (see post separation results section below for an explanation of results). As noted previously, Test Site #6 may not have performed to its true capability on the day of the test. Due to a malfunction in the line, the electroless copper bath was controlled by manual lab analysis instead of by the usual single-channel controller.

**Figure 4.2 Carbon - IST Cycles to Fail vs. Resistance**

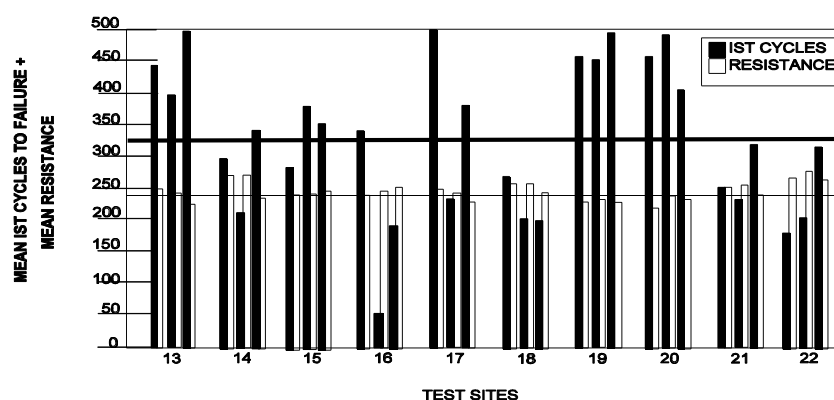


As shown in Figure 4.2, both carbon test sites had at least two panels that met or exceeded the mean performance.

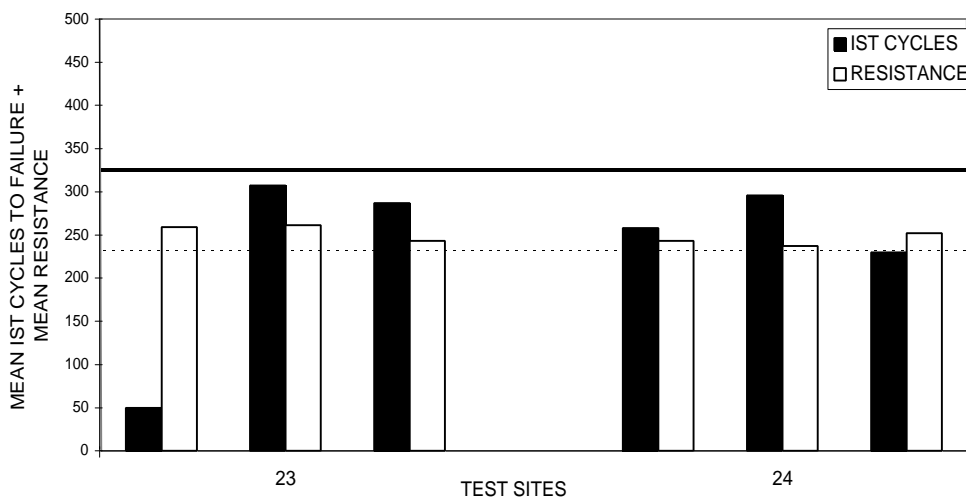
**Figure 4.3 Graphite - IST Cycles to Fail vs. Resistance**



All three graphite test sites had at least one panel that met or exceeded mean performance, as shown in Figure 4.3.

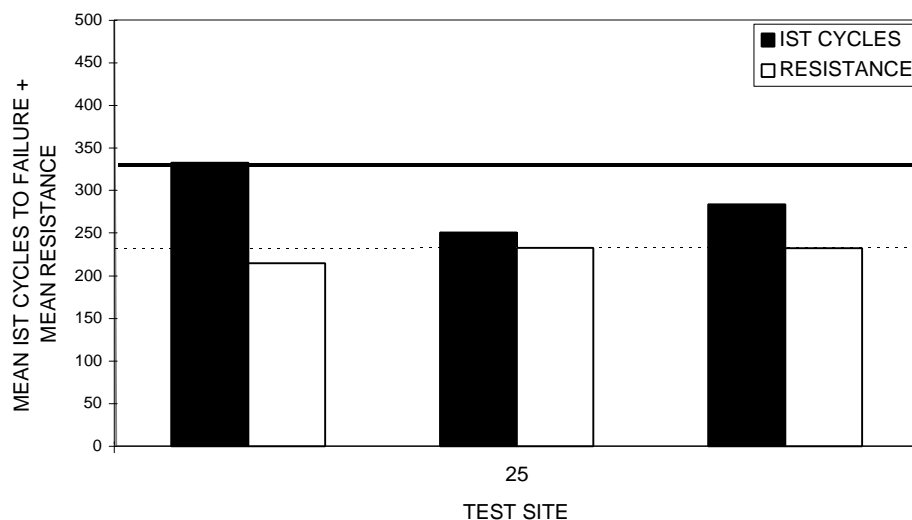
**Figure 4.4 Palladium - IST Cycles to Fail vs. Resistance**

As shown in Figure 4.4, most palladium test sites had at least one panel that met or exceeded the mean performance. Three test sites did not. Those test sites that did not achieve the mean performance exhibited either high resistance or post separation.

**Figure 4.5 Non-Formaldehyde Electroless Copper - IST Cycles to Fail vs. Resistance**

Neither non-formaldehyde electroless copper test site met or exceeded mean performance, as shown in Figure 4.5. Test Site #23 exhibited a high degree of post separation (see post separation results section below for an explanation of results).

**Figure 4.6 Conductive Polymer - IST Cycles to Fail vs. Resistance**



As shown in Figure 4.6, the single conductive polymer test site had one panel that met or exceeded the mean performance.

### Post Separation Testing Results

IST determines post interconnect performance (post separation) simultaneously with the PTH cycles to failure performance. The failure criteria for post separation has not been established. Further work is in progress with the IPC to create an accept/reject criteria. For this study, the IST rejection criteria is based on a 15 milliohm resistance increase derived from the mean resistance degradation measurement for all 300 coupons tested.

A reliable post interconnect should measure minimal resistance degradation throughout the entire IST. Low degrees of degradation (<15 milliohms) are common and relate to the fatigue of the internal copper foils. Resistance increases greater than 50 milliohms were reported as 50 milliohms. This was done in order to avoid skewing results.

The mean resistance degradation of the post interconnect is determined at the time the PTH failed. The readings (in milliohms) for the post interconnect and the standard deviations for each test site (sample size = 12 coupons from each site) and for each MHC technology are shown in Tables 4.10 and 4.11, respectively.



**Table 4.10 Mean Resistance Degradation of Post Interconnect, by Test Site  
(in milliohms)**

Test Site # and MHC Technology Type	Post Degradation	Standard Deviation
1 Electroless Copper	13.1	3.5
2 Electroless Copper	17.2	12.9
3 Electroless Copper	6.6	3.7
4 Electroless Copper	6.7	2.7
5 Electroless Copper	3.8	2.4
6 Electroless Copper	34.8	13.1
7 Electroless Copper	4.1	4.6
8 Carbon	2.8	2.9
9 Carbon	2	2.5
10 Graphite	5.2	3.9
11 Graphite	8	8.1
12 Graphite	16	15
13 Palladium	9.5	4.7
14 Palladium	2.8	2.6
15 Palladium	7.9	7.4
16 Palladium	32.2	18.1
17 Palladium	0.8	1.8
18 Palladium	7.6	6.4
19 Palladium	4.7	3.3
20 Palladium	13.7	5.6
21 Palladium	40.5	11.3
22 Palladium	4.5	2.6
23 Non-Formaldehyde Electroless Copper	47.9	7.2
24 Non-Formaldehyde Electroless Copper	4.2	1.9
25 Conductive Polymer	2.8	1.8

**Table 4.11 Mean Resistance Degradation of Post Interconnect, by MHC Technology**

MHC Technology Type	Post Degradation	Standard Deviation
Electroless Copper	12.3	12.6
Carbon	2.4	2.7
Conductive Polymer	2.75	1.8
Graphite	9.7	10.8
Non-Formaldehyde Electroless Copper	26	22.9
Palladium	12.4	14.3

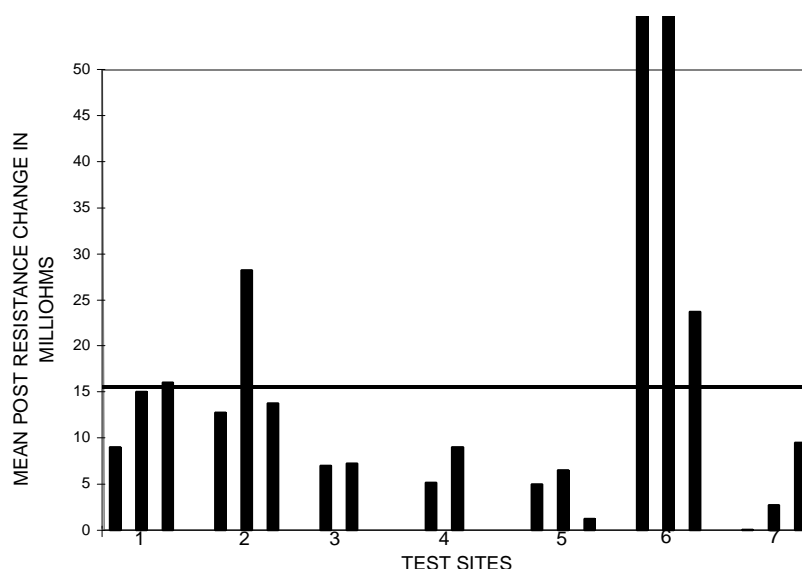
High standard deviations indicate that high levels of variability exist within and among test sites and within an MHC technology.

## 4.1 PERFORMANCE DEMONSTRATION RESULTS

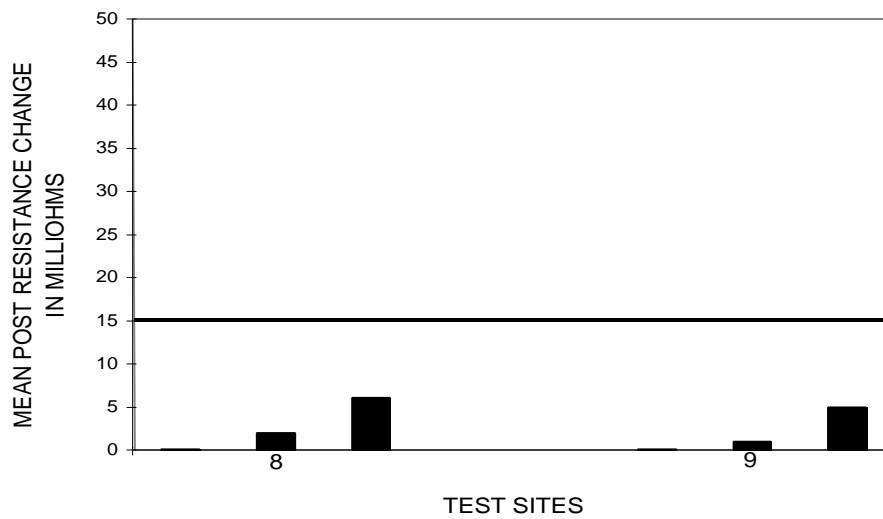
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Figures 4.7 through 4.12 identify the mean (average of four coupons per panel) IST post resistance degradation results. The reference line on each graph identifies the mean resistance degradation measurement for all 300 coupons tested (15 milliohms). If the mean resistance degradation column is above the reference line, the panel had coupons that exhibited post separation. The post resistance change was the value recorded at the point where the PTH (barrel) failed.

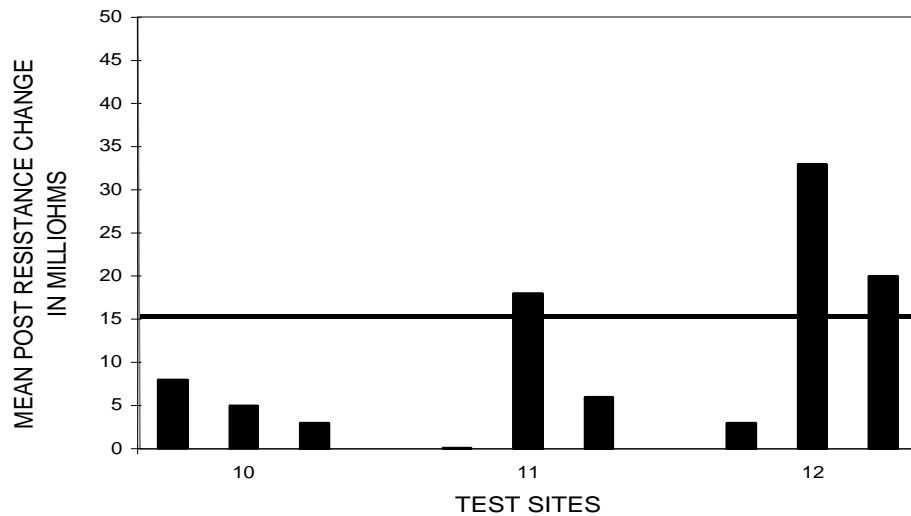
**Figure 4.7 Electroless Copper - Post Resistance Degradation**



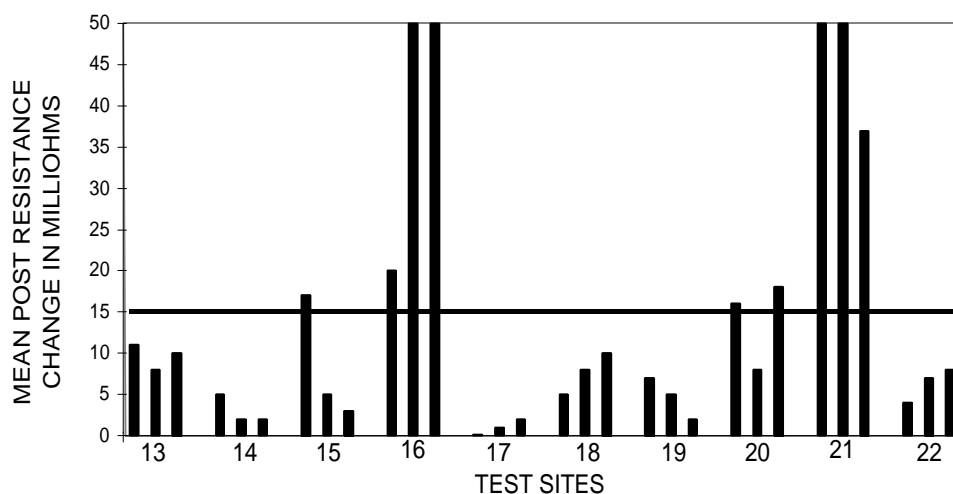
As shown in Figure 4.7, two of the seven electroless copper test sites had at least one panel that exhibited post separation. All three panels from Test Site #6 clearly exhibited gross post separation. Both test methods for post separation failed all panels from Test Site #6. As noted previously, Test Site #6 may not have performed to its true capability on the day of the test. Due to a malfunction in the line, the electroless copper bath was controlled by manual lab analysis instead of by the usual single-channel controller.

**Figure 4.8 Carbon - Post Resistance Degradation**

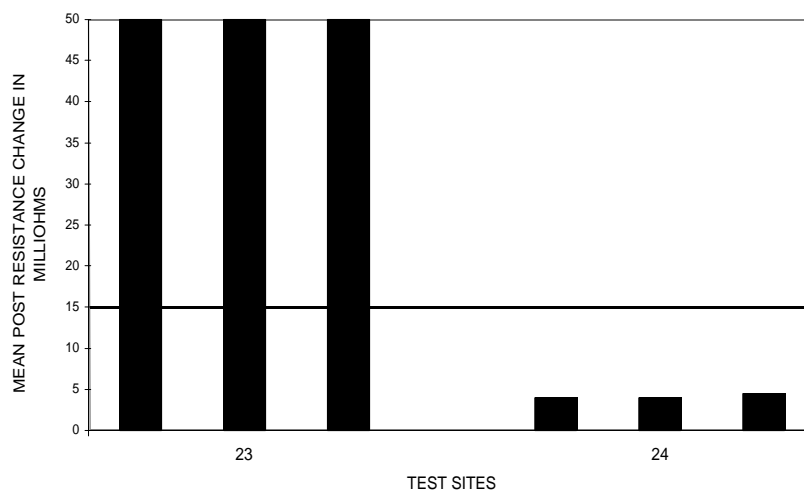
No post separation was detected on any carbon panels, as shown in Figure 4.8.

**Figure 4.9 Graphite - Post Resistance Degradation**

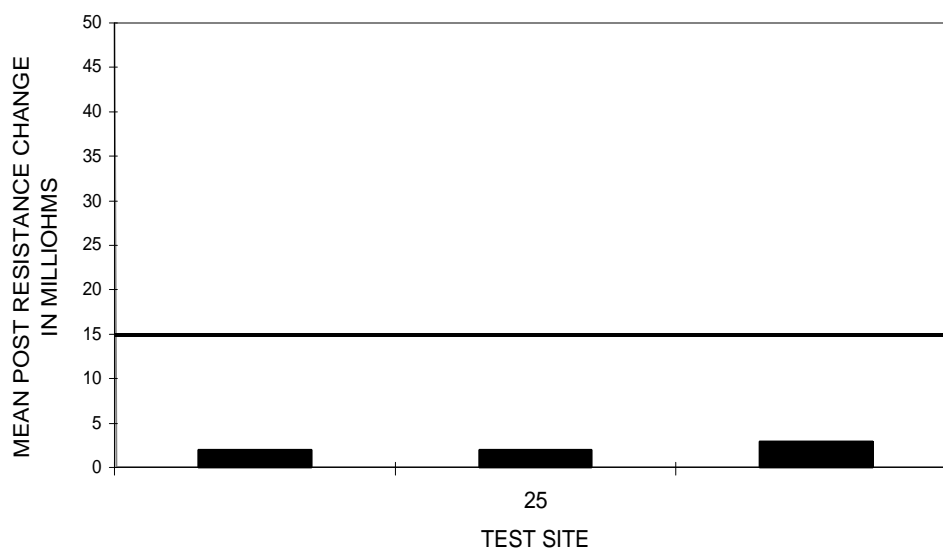
As shown in Figure 4.9, two of the three graphite test sites had at least one panel that exhibited post separation.

**Figure 4.10 Palladium - Post Resistance Degradation**

As shown in Figure 4.10, four of the ten palladium test sites had at least one panel that exhibited post separation. Test Site #16 and Test Site #21 clearly exhibited gross post separation.

**Figure 4.11 Non-Formaldehyde Electroless Copper - Post Resistance Degradation**

As shown in Figure 4.11, all three panels for non-formaldehyde electroless copper Test Site #23 clearly exhibited gross post separation.

**Figure 4.12 Conductive Polymer - Post Resistance Degradation**

No post separation was detected on any conductive polymer panels, as shown in Figure 4.12.

#### 4.1.6 Comparison of Microsection and IST Test Results

Microsection and IST were run independently, and test results were not shared until both sets of data were completed and delivered to EPA. To illustrate the consistency of the test results, Table 4.12 identifies both test methods and their results for post separation detection.

“Y” or “N” (yes or no) denote whether post separation was detected on any coupon or panel from each test site. The “panels affected” column refers to how many of the panels within each test site exhibited post separation. Test Site #17 was the only site with post separation found in the microsection but not on IST.

Post separation results indicated percentages of post separation that were unexpected by many members of the industry. It was apparent that all MHC technologies, including electroless copper, are susceptible to this type of failure. The results of this study further suggest that post separation may occur in different degrees. The level of post separation may play a role in determining product performance; however, the determination of levels of post separation remains to be discussed and confirmed by the PWB industry.

#### 4.1 PERFORMANCE DEMONSTRATION RESULTS

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**Table 4.12 IST/Microsection Data Correlation**

Test Site #	Microsection	Panels Affected	IST	Panels Affected
1	N	0	N	0
2	Y	3	Y	3
3	N	0	N	0
4	N	0	N	0
5	N	0	N	0
6	Y	3	Y	3
7	N	0	N	0
8	N	0	N	0
9	N	0	N	0
10	N	0	N	0
11	Y	2	Y	1
12	Y	3	Y	2
13	N	0	N	0
14	N	0	N	0
15	Y	1	Y	1
16	Y	3	Y	3
17	Y	1	N	0
18	Y	2	Y	2
19	N	0	N	0
20	Y	3	Y	2
21	Y	3	Y	3
22	N	0	N	0
23	Y	3	Y	3
24	N	0	N	0
25	N	0	N	0

## 4.2 COST ANALYSIS

Operating an efficient and cost-effective manufacturing process with strict control of material and production costs is the goal of every successful company. Fueled by consumer demand for smaller and lighter electronics, rapid and continuous advances in circuit technology make this goal a necessity for PWB manufacturers attempting to compete in today's global marketplace. The higher aspect-ratio holes and tighter circuit patterns on current PWBs are forcing manufacturers to continually evaluate and eventually replace aging manufacturing processes that are unable to keep up with the ever-increasing technology threshold. When coupled with the typically slim profit margins of PWB manufacturers, these process changes represent a major capital investment to a company and emphasize the importance of selecting an efficient, cost-effective process that will allow the company to remain competitive. As a result, manufacturers are seeking comprehensive and more detailed cost data before investing in alternative processes.

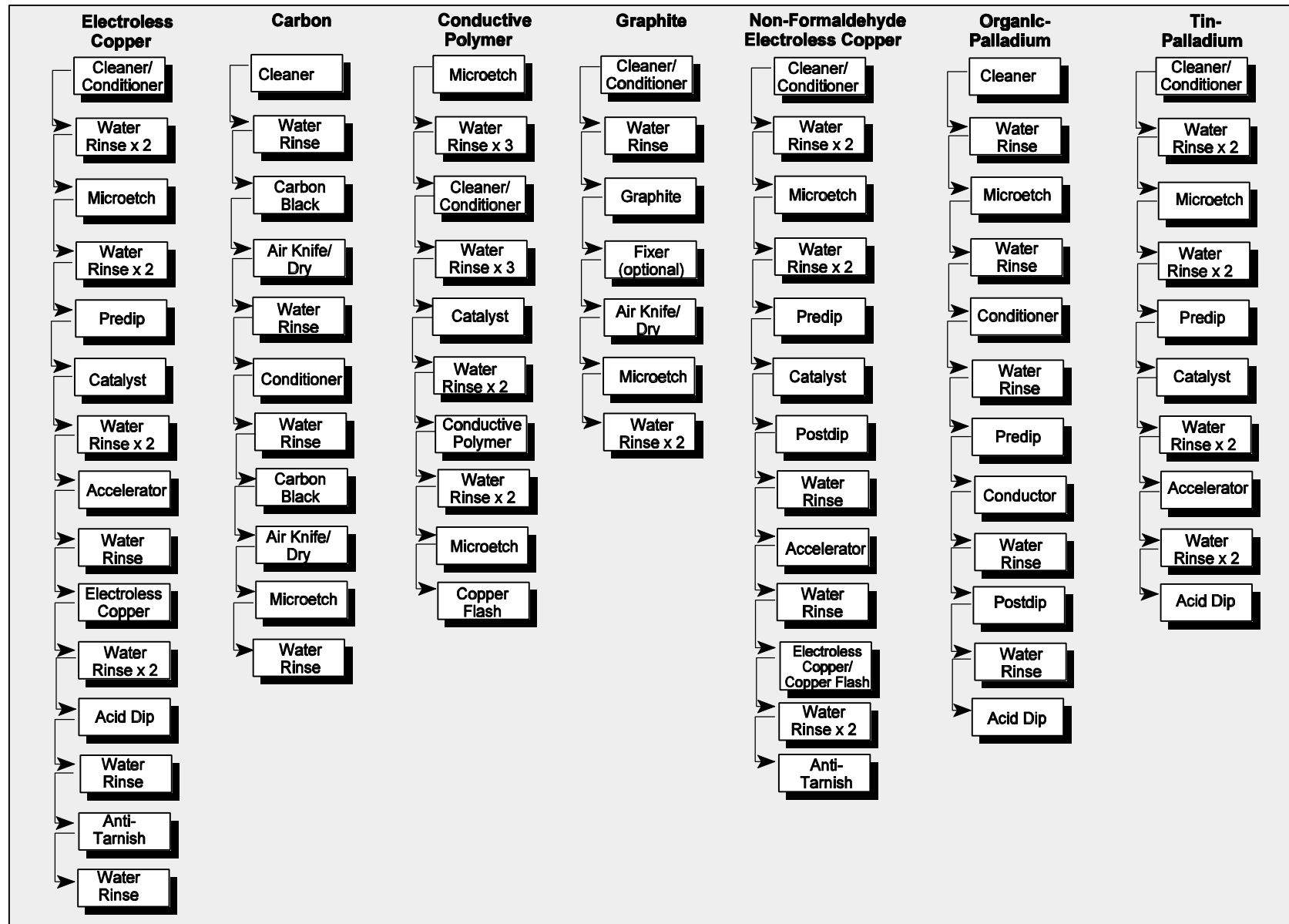
This section presents a comparative cost analysis of the MHC technologies. Costs were developed for each technology and equipment configuration (vertical, immersion-type equipment, or horizontal, conveyorized equipment) for which data were available from the IPC Workplace Practices Questionnaire and Performance Demonstration. Table 4.13 presents the processes (alternatives and equipment configurations) evaluated.

**Table 4.13 MHC Processes Evaluated in the Cost Analysis**

MHC Alternative	Non-Conveyorized	Conveyorized
Electroless Copper	✓	✓
Carbon		✓
Conductive Polymer		✓
Graphite		✓
Non-Formaldehyde Electroless Copper	✓	
Organic-Palladium	✓	✓
Tin-Palladium	✓	✓

Costs were analyzed using a cost model developed by the University of Tennessee Department of Industrial Engineering. The model employs generic process steps and functional groups (see Section 2.1, Chemistry and Process Description of MHC Technologies) and typical bath sequences (see Section 3.1, Source Release Assessment) for each process alternative. Figure 4.13 presents the generic process steps and typical bath sequences. To develop comparative costs on a \$/surface square foot (ssf) basis, the cost model was formulated to calculate the cost of performing the MHC function on a job consisting of 350,000 ssf. This is the average annual throughput for facilities in the IPC Workplace Practices Questionnaire database. The cost for each process is compared to a generic non-conveyorized electroless copper process, defined here as the baseline process.

Figure 4.13 Generic Process Steps and Typical Bath Sequences of MHC Technologies





The overall objective of this analysis was to determine the comparative costs of the MHC technologies using a cost model that adheres to fundamental principles of cost analysis. Other objectives were to make the analysis flexible and to consider environmental costs. The cost model was designed to estimate the comparative costs of fully operational MHC process lines. It does not estimate start-up costs for a facility switching to an alternative MHC technology or the cost of other process changes that may be required to implement a new MHC technology. Section 4.2.1 gives an overview of the cost methodology. Section 4.2.2 presents simulation model results. Section 4.2.3 describes details of the cost methodology and presents sample cost calculations. Section 4.2.4 contains analysis results, while Section 4.2.5 presents a sensitivity analysis of the results. Section 4.2.6 presents conclusions.

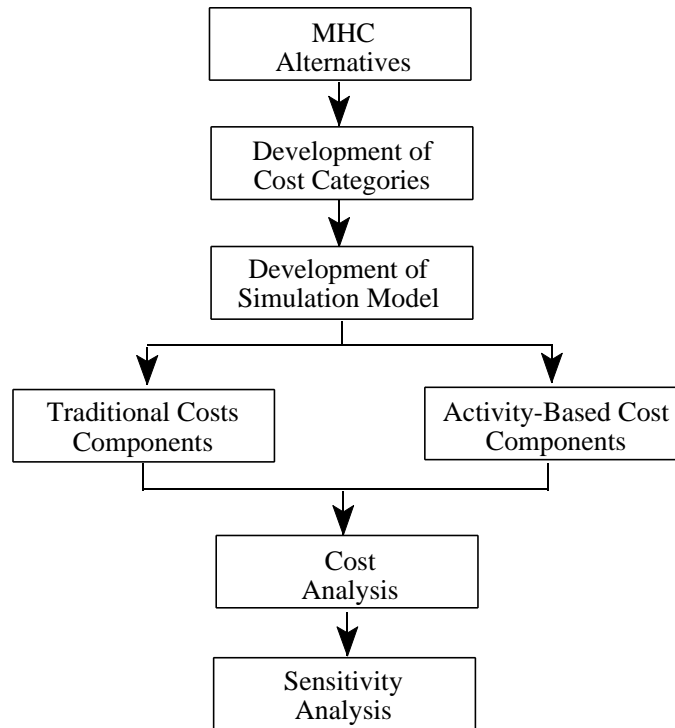
#### **4.2.1 Overview of the Cost Methodology**

The costs of the MHC technologies were developed by identifying the steps in each process, breaking each step down into its cost components, and determining the cost of each component. Component costs were determined utilizing traditional costing mechanisms, computer simulation, and ABC. Computer simulation was used to replicate each of the MHC processes to determine the time required to complete the specified job and other job-specific metrics. ABC is a cost accounting method that allocates indirect or overhead costs to the products or processes that actually incur those costs. Activity-based costs are determined by developing bills of activities (BOAs) for tasks essential to the process. A BOA is a listing of the component activities involved in the performance of a certain task, together with the number of times each component activity is performed. The BOA determines the cost of a task by considering the sequence of actions and the resources utilized while performing that task.

#### **Framework for the Cost Formulation**

Figure 4.14 presents the hybrid cost formulation framework used in this analysis. The first step in the framework was to develop or define the alternatives to be evaluated. The generic process descriptions, chemical baths, typical bath sequences, and equipment configurations were defined in Table 4.13 and Figure 4.13. This information was used to identify critical variables and cost categories that needed to be accounted for in the cost analysis. Cost categories were analyzed to identify the data required to calculate the costs (i.e., unit costs, utilization or consumption rates, criteria for performing an activity, such as chemical bath replacement, the number of times an activity is performed, etc.). For each process, a computer simulation was then developed using ARENA® computer simulation software and information derived from the cost components. The simulations were designed to model a MHC manufacturing job consisting of 350,000 ssf.

**Figure 4.14 Hybrid Cost Formulation Framework**



Simulation modeling provides a number of advantages to the cost analysis, including the following:

- Simulation modeling can replicate a production run on the computer screen, allowing an analyst to observe a process when the actual process does not exist. In this case, the generic MHC technologies, as they are defined in Figure 4.13, may not exist within any one facility.
- Simulation allows for process-based modifications and variations, resulting in inherent flexibility within the system. Simulation models can be designed to vary the sequence of operations, add or delete operations, or change process times associated with operations, materials flows, and other variables.
- Data gathered from PWB manufacturers, chemical suppliers, and the Performance Demonstration have some data gaps and inconsistencies. However, these data must be aggregated to develop comparative costs of the generic MHC alternatives. Thus, data collected from one or more facilities may not fully represent a generic MHC alternative or group of alternatives. Process simulation based on fundamental assumptions and data helps clear up data inconsistencies and fill data gaps.
- Simulation enables one to study the sensitivity of critical performance measures to changes in underlying input variables. Constant input variables may be modified in the sensitivity analysis to determine the uncertainty (in terms of probability distributions) associated with these input variables.

Direct results of the simulation model and results derived from simulation outputs include the following:

- The amount of time the MHC line operates to produce the job.
- The number of times an activity is performed during the course of the job.
- Consumption rates (e.g., water, energy, and chemical consumption).
- Production rates (e.g., wastewater generation).

Simulation results were combined with traditional cost components to adjust these costs for the specified job. An example of this is the determination of equipment cost. Simulation results were used to calculate a utilization ratio (UR), defined as the amount of time in days required to produce 350,000 ssf divided by one operating year (defined as 250 days). Annualized equipment costs were determined utilizing industry sources for equipment price and depreciation guidelines from the Internal Revenue Service. These costs were multiplied by the UR to determine the equipment costs for the job being evaluated.

Activity-based costs were determined by combining simulation results for the frequency of activities with the cost of an activity developed on a BOA. For example, the activity costs of replacing a particular bath were determined by developing a BOA, developing costs for each activity on the BOA, and multiplying these costs by the number of bath replacements required to complete a job of 350,000 ssf. In this manner, the overall analysis combines traditional costs with simulation outputs and activity-based costs. The effects of critical variables on the overall costs were then evaluated using sensitivity analysis.

### **Cost Categories**

Table 4.14 summarizes the cost components considered in this analysis, gives a brief description of each cost component and key assumptions, and lists the primary sources of data for determining the costs. Section 4.2.3 gives a more detailed accounting of the cost components, including sample cost calculations for each component.

In addition to traditional costs, such as capital, production, and maintenance costs, the cost formulation identifies and captures some environmental costs associated with the alternatives. In this regard, both simulation and ABC assist in analyzing the impact of the MHC alternatives on the environment. Specifically, the amounts of energy and water consumed as well as the amount of wastewater generated are determined for each MHC alternative. Environmental costs that could not be quantified include wastewater treatment and solid waste disposal costs. Also, the costs of defective boards and the consequent waste of resources were not quantified. These costs are discussed in more detail, below.

## 4.2 COST ANALYSIS

**Table 4.14 Cost Components**

Cost Category	Component	Description of Cost Component	Sources of Cost Data
Capital Cost	Primary Equipment	Annualized cost of equipment with throughput capacity of 100 panels/hr times UR <sup>a</sup> ; assumes 10 year equipment life and straight-line depreciation.	Vendor quote for equipment cost; time to complete job from simulation.
	Installation	Annualized cost of delivering and installing equipment times UR <sup>a</sup> ; assumes 10 year equipment life and straight-line depreciation.	Vendor quote for installation costs; time to complete job from simulation.
	Facility	Annualized cost of floor space required to operate MHC equipment times UR <sup>a</sup> ; assumes 25 year facility life and straight-line depreciation.	Floor space requirements from Workplace Practices Survey; unit cost for industrial floor space from published sources.
Material Cost	Process Chemicals	Costs of chemicals used in initial bath setup and to replace spent process baths.	Vendor quotes for chemical product cost; bath sizes from Workplace Practices Survey; bath replacement criteria from supplier data; number of bath replacements required for job from simulation.
Utility Cost	Water	Water consumption costs based on number of rinse tanks per process line; daily water usage per tank, and days to complete job.	Number of rinse tanks and daily water usage per tank from Section 5.1, Resource Conservation; days to complete job from simulation.
	Electricity	Electricity costs based on daily electricity consumption by MHC equipment and days to complete job.	Daily electricity consumption from Section 5.2, Energy Impacts; days to complete job from simulation.
	Natural Gas	Natural gas consumption based on daily natural gas consumption from drying ovens (carbon and graphite processes only) and days to complete job.	Daily natural gas consumption from Section 5.2, Energy Impacts; days to complete job from simulation.
Wastewater Cost	POTW Permit	Cost for permit to discharge wastewater to publicly-owned treatment works (POTW).	Not quantified; assumed to be the same for all alternatives.
	Wastewater Pretreatment Cost	Cost to pretreat wastewater prior to discharge to POTW.	Not quantified; pretreatment costs are expected to differ significantly among the alternatives, but insufficient data were available to reliably estimate these costs.
	Wastewater Discharge Costs	Fees for wastewater discharge assessed by local utility.	Quantity of wastewater discharged assumed equal to water usage; discharge fees based on fees charged by Knoxville, Tennessee Utility Board (KUB).

Cost Category	Component	Description of Cost Component	Sources of Cost Data
Production Cost	Labor	Labor costs for line operator, excluding labor costs for maintenance activities (included under maintenance costs). Assumes one line operator per day per conveyORIZED process, 1.1 line operators per day per non-conveyORIZED process.	Number of line operators based on Workplace Practices Survey data and site visits; days to produce job from simulation; labor rate = \$10.22/hr based on published data.
	Transportation of Materials	Cost to transport chemicals required for bath replacement from storage to process line.	Cost of transporting materials from BOA; number of bath replacements required from simulation.
Maintenance Cost	Bath Clean-up	Labor and materials (excluding replacement chemicals) costs to clean up a chemical tank during bath replacement.	Cost to clean up tank from BOA; number of bath cleanups (replacements) required from simulation.
	Bath Setup	Labor and equipment costs to set up a chemical tank after bath replacement.	Cost to set up bath from BOA; number of bath setups required from simulation.
	Sampling and Analysis	Labor and materials costs for sampling and analysis of chemical baths.	Assumes analytical work done in-house. Cost for one activity from BOA; annual number of samples from Workplace Practices Survey adjusted using UR <sup>a</sup> .
	Filter Replacement	Labor costs for replacing bath filters.	Labor cost for one activity from BOA; annual number of filters replaced from Workplace Practices Survey adjusted using UR <sup>a</sup> .
Waste Disposal Cost	Sludge Disposal	Disposal cost to recycle or dispose of sludge from wastewater treatment.	Not quantified; sludge disposal costs are expected to differ significantly among the alternatives, but insufficient data were available to reliably estimate these costs. Factors affecting sludge disposal cost include the characteristics of the sludge (i.e., metal content, percent solids, waste classification, etc.) and the amount of sludge generated.
	Filter Disposal	Disposal cost to recycle or dispose of bath filters.	Not quantified; filter disposal costs are expected to differ significantly among the alternatives, but insufficient data were available to reliably estimate these costs. Factors affecting filter disposal cost include the waste classification of the filter, the size (weight and volume) of the filter, and the number of waste filters generated.
Quality Cost	Defective Boards	Costs of defective boards due to failure of MHC process lines to adequately make holes conductive.	Not quantified; assumed equal among the alternatives. Performance Demonstration showed that all alternatives can work at least as well as the baseline process as long as they are operated according to supplier specifications.

<sup>a</sup> UR = utilization ratio = the time in days required to process 350,000 ssf ÷ one operating year (250 days).

**Wastewater Treatment and Sludge Disposal Costs.** PWB manufacturing consists of a number of process steps (see Section 1.2.3 for an overview of rigid multi-layer PWB manufacturing). In addition to the MHC process line, these steps include electroplating operations and other steps which consume large quantities of rinse water and, consequently, generate large quantities of wastewater. Most PWB manufacturers combine the effluents from various process lines into one wastewater stream which is treated on-site in a continuous process prior to discharge. As part of the *Pollution Prevention and Control Survey* (EPA, 1995a), PWB manufacturers were asked to provide the following about their on-site wastewater treatment facility:

- A process flow diagram for wastewater treatment.
- The quantity of sludge generated from wastewater treatment.
- The percent solids of the sludge.
- The costs of on-site wastewater treatment.
- The method and costs of sludge recycle and disposal.

Capital costs for wastewater treatment ranged from \$1.2 million for a system purchased in 1980 with a capacity of 135 gallons per minute (gpm) to \$4,000 for a system purchased in 1987 with a capacity of nine gpm. Costs for operating an on-site wastewater treatment system were as high as 3.1 percent of total annual sales. The median cost for wastewater treatment operation was 0.83 percent and the average was 1.02 percent of annual sales.

Wastewater treatment sludges from PWB electroplating operations are classified as an F006 hazardous waste under the Resources Conservation and Recovery Act (RCRA); most facilities combine effluents from the electroplating line with other process wastewaters. Eighty-eight percent of respondents to the Survey reported that wastewater treatment sludges are sent to an off-site recycling facility to recover the metals. The average and median costs for off-site recovery of sludge were \$0.48/lb and \$0.21/lb, respectively. In general, the lower costs experienced by some respondents compared to others were due to larger-size shipments and shorter distances to the recycling sites. In some cases, respondents whose sludge had a higher solids content also reported lower costs; dewatered sludge has a higher recovery value.

Eighty-six percent of Survey respondents used an electroless copper MHC process, 14 percent used a palladium-based process (the Survey did not distinguish between tin- and organic-palladium processes), and one respondent used a graphite process. None of the other MHC alternatives were represented in the Survey.

The IPC Workplace Practices Questionnaire attempted to characterize costs by collecting information about the percent the MHC line contributes to overall wastewater and sludge generation rates. However, most manufacturers were unable to provide this information and the data that were reported were of variable to poor quality.

Since the MHC line is only one of several process lines that discharge effluent to wastewater treatment and because little or no information is available on the contribution of the MHC line to overall wastewater effluents, on-site wastewater treatment and sludge disposal costs could not be reliably estimated. However, costs of wastewater treatment and sludge disposal are expected to differ significantly among the alternatives. For example, the presence of the chelator

EDTA in electroless copper wastewater discharges makes these effluents more difficult to treat. However, complexing agents, such as the ammonia found in other PWB manufacturing steps, also adversely affect the treatability of wastewater.

**Other Solid Waste Disposal Costs.** Two other types of solid wastes were identified that could have significantly different waste disposal costs among the alternatives: filter disposal cost and defective boards disposal costs. Table 4.15 presents the number of filters that would be replaced in each process during a job of 350,000 ssf. These data are based on data from the IPC Workplace Practices Questionnaire and a UR calculated for each process from simulation results. (Simulation results are discussed further in Section 4.2.2.) While these results illustrate that the number of waste filters generated by the alternatives differ significantly, no information is available on the characteristics of the filters used in alternative processes. For example, the volume or mass of the filters and waste classification of the filters (hazardous or non-hazardous) would significantly affect the unit cost for disposal. Therefore, filter disposal costs were not estimated.

**Table 4.15 Number of Filter Replacements by MHC Process**

MHC Process	Filter Replacements per Year <sup>a</sup>	Filter Replacements per Job <sup>b</sup>
Electroless Copper, non-conveyorized (BASELINE)	100	160
Electroless Copper, conveyorized	100	35
Carbon, conveyorized	20	7
Graphite, conveyorized	103	52
Conductive Polymer, conveyorized	74	21
Non-Formaldehyde Electroless Copper, non-conveyorized	17	12
Organic-Palladium, non-conveyorized	50	22
Organic-Palladium, conveyorized	50	16
Tin-Palladium, non-conveyorized	74	35
Tin-Palladium, conveyorized	74	19

<sup>a</sup> 90th percentile data based on Workplace Practices Survey data. Data not adjusted for throughput or to account for differing maintenance policies at individual PWB manufacturing facilities.

<sup>b</sup> Based on simulation results for a job of 350,000 ssf.

The number of defective boards produced by an alternative has significance not only from the standpoint of quality costs, but also from the standpoint of waste disposal costs. Clearly, a higher defect rate leads to higher scrap and, therefore, waste of resources. However, the Performance Demonstration showed that each of the alternatives can perform as well as the electroless copper process if operated according to specifications. Thus, for the purposes of this analysis, no differences would be expected in the defect rate or associated costs of the alternatives.

### **Simulation Model Assumptions and Input Values**

Appendix G presents a graphic representation of the simulation models developed for each of the MHC alternatives. The assumptions used to develop the simulation models and

## 4.2 COST ANALYSIS

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model input values are discussed below.

**Assumptions.** Several assumptions used in the simulation model are based on the characteristics of a model facility presented in the Source Release Assessment and Exposure Assessment (Sections 3.1 and 3.2, respectively). Assumptions include the following:

- The facility operates an MHC line 250 days/year, one shift/day. Many facilities operate two shifts, but the Exposure Assessment and this analysis use first shift data as representative. This assumption could tend to underestimate labor costs for companies that pay higher rates to second shift workers. Or it could tend to overestimate equipment costs for a company running two shifts and using equipment more efficiently. However, since this assumption is used consistently across alternatives, the effects on the comparative cost results are expected to be minor.
- The MHC process line operates an average of 6.8 hrs/shift.
- The MHC line is down at least 1.2 hours per day for start-up time and for maintenance, including lubricating of equipment, sampling of baths, and filter replacement.
- Additional down time occurs when the MHC line is shut down to replace a spent or contaminated bath.
- PWB panels that have been processed up to the MHC step are available whenever the MHC process line is ready for panels.
- If a chemical bath is replaced at the end of the day, such that the amount of time required to replace the bath exceeds the time remaining in the shift hours, employees will stay after hours and have the bath ready by the beginning of the next shift.
- The entire MHC process line is shut down whenever a bath requires replacing, but partially processed racks or panels are finished before the line is shut down.
- The MHC process only shuts down at the end of a shift and for bath replacement.
- The process is empty of all panels or racks at the end of each shift and starts the process empty at the beginning of a shift.

Further simulation assumptions have to be defined separately for conveyORIZED and non-conveyORIZED systems. ConveyORIZED MHC process assumptions are as follows:

- The size of a panel is 17.7" x 22.9" (from IPC Workplace Practices Questionnaire data for conveyORIZED processes).
- Panels are placed on the conveyor whenever space on the conveyor is available, and each panel requires 18" (including space between panels).
- Conveyor speed is constant, thus, the volume (gallons) of chemicals in a bath varies by bath type (i.e., microetch, conditioner, etc.) and with the length of the process step (e.g., bath or rinse tank) to provide the necessary contact time (see Table 4.16 for bath volumes).
- The conveyor speed, cycle time, and process down time are critical factors that determine the time to complete a job.



**Table 4.16 Bath Volumes Used for Conveyorized Processes**

Chemical Bath	Bath Volume by MHC Alternative (gallons)					
	Electroless Copper	Carbon	Conductive Polymer	Graphite	Organic-Palladium	Tin-Palladium
Cleaner/Conditioner	65	NA	65	65	NA	65
Cleaner	NA	44	NA	NA	44	NA
Carbon	NA	128	NA	NA	NA	NA
Graphite	NA	NA	NA	37	NA	NA
Conditioner	NA	56	NA	NA	56	NA
Polymer	NA	NA	26	NA	NA	NA
Microetch	64	64	64	64	64	64
Predip	50	NA	NA	NA	50	59
Catalyst	139	NA	139	NA	NA	139
Accelerator	80	NA	NA	NA	NA	80
Conductor	NA	NA	NA	NA	108	NA
Electroless Copper	185	NA	NA	NA	NA	NA
Post Dip	NA	NA	NA	NA	45	NA
Acid Dip	79	NA	NA	NA	79	79
Anti-Tarnish	39	NA	NA	NA	NA	NA

NA: Not Applicable.

Non-conveyorized MHC process assumptions are as follows:

- The average volume of a chemical bath is 75 gallons (from IPC Workplace Practices Questionnaire data for non-conveyorized processes).
- Only one rack of panels can be placed in a bath at any one time.
- A rack contains 20 panels (based on IPC Workplace Practices Questionnaire data, including the dimensions of a bath, the size of a panel, and the average distance between panels in a rack).
- The size of a panel is 16.2" x 21.5" to give 96.8 ssf per rack.
- The frequency at which racks are entered into the process is dependent upon the bottleneck or rate limiting step.
- The duration of the rate limiting step, cycle time, and process down time are critical factors that determine the time to complete a job.

**Inputs Values.** Input values for the critical factors identified above (cycle time, down time, and conveyor speed for conveyorized processes, and cycle time, down time, and duration of rate limiting step for non-conveyorized processes) were developed from IPC Workplace Practices Questionnaire data and Product Data Sheets prepared by suppliers which describe how to mix and maintain chemical baths. Tables 4.17 and 4.18 present time-related inputs to the simulation models for non-conveyorized and conveyorized processes, respectively.

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**Table 4.17 Time-Related Input Values for Non-Conveyorized Processes<sup>a</sup>**

Non-Conveyorized MHC Alternative	Time Required to Replace a Bath <sup>b</sup> (minutes)	Rate Limiting Bath	Time in Rate Limiting Bath <sup>c</sup> (minutes)	Process Cycle Time <sup>c</sup> (minutes)
Electroless Copper	180	Electroless Copper	34	48
Non-Formaldehyde Electroless Copper	30	Electroless Copper	16	51
Organic-Palladium	180	Accelerator	9.2	30
Tin-Palladium	108	Conductor	5.3	52

<sup>a</sup> Values are averages or 90th percentile data from the IPC Workplace Practices Questionnaire and may represent chemical products from more than one supplier. For example, five suppliers of electroless copper chemical products participated in the project. Input values may underestimate or overestimate those of any one facility, depending on factors such as individual operating procedures, the chemical or equipment supplier, and the chemical product used.

<sup>b</sup> 90th percentile value used in the Exposure Assessment from IPC Workplace Practices Questionnaire data (see Section 3.2). Used to calculate down time.

<sup>c</sup> Average values from the IPC Workplace Practices Questionnaire.

**Table 4.18 Time-Related Input Values for Conveyorized Processes<sup>a</sup>**

Conveyorized MHC Alternative	Time Required to Replace a Bath <sup>b</sup> (minutes)	Length of Conveyor <sup>c</sup> (feet)	Process Cycle Time <sup>c</sup> (minutes)	Conveyor Speed <sup>d</sup> (ft/min)
Electroless Copper	180	71	15	4.7
Carbon	180	31	13	2.4
Conductive Polymer	180	34	8.0	4.3
Graphite	219	27	7.8	3.5
Organic-Palladium	108	50	15	3.3
Tin-Palladium	180	47	8.6	5.5

<sup>a</sup> Values are averages or 90th percentile data from the IPC Workplace Practices Questionnaire and may represent chemical products from more than one supplier. For example, five suppliers of electroless copper chemical products participated in the project. Input values may underestimate or overestimate those of any one facility, depending on factors such as individual operating procedures, the chemical or equipment supplier, and the chemical product used.

<sup>b</sup> 90th percentile value used in the Exposure Assessment from IPC Workplace Practices Questionnaire data (see Section 3.2). Used to calculate down time.

<sup>c</sup> Average values from IPC Workplace Practices Questionnaire.

<sup>d</sup> Conveyor speed = length of conveyor ÷ process cycle time.

The input values for the time required to replace a bath time (in Tables 4.17 and 4.18) are used together with bath replacement criteria in the calculation of down time. Suppliers provide instructions with their products (called Product Data Sheets for the purposes of this project) that describe when a bath should be replaced because it is expected to be spent or too contaminated to be used. These replacement criteria are usually given in one of three forms:

- As a bath capacity in units of ssf per gallon of bath.
- As a concentration-based criterion that specifies an upper concentration limit for contaminants in the bath, such as grams of copper per liter in the microetch bath.
- As elapsed time since bath creation.

Bath replacement criteria submitted by suppliers were supplemented with IPC Workplace Practices Questionnaire data and reviewed to determine average criteria for use in the simulation models. Criteria in units of ssf/gallon were preferred because these can be correlated directly to the volume of a bath. Once criteria in ssf/gallon were determined, these were converted to units of racks per bath replacement for non-conveyorized processes and panels per bath replacement for conveyorized processes. The converted values were used as inputs to the simulation models. As an example, Table 4.19 presents bath replacement criteria used to calculate input values for electroless copper processes. Appendix G presents the different bath replacement criteria recommended by chemical suppliers, and the input values used in this analysis.

**Table 4.19 Bath Replacement Criteria for Electroless Copper Processes**

<b>Chemical Bath</b>	<b>Bath Replacement Criteria<sup>a</sup> (ssf/gal)</b>
Cleaner/Conditioner	510
Microetch	250
Predip	540
Catalyst	Replace once per year
Accelerator	280
Electroless Copper	430
Acid Dip	675
Anti-Tarnish	325

<sup>a</sup> Values were selected from data provided by more than one electroless copper chemical supplier. To convert to units of racks per bath replacement for non-conveyorized processes, multiply by 75 gallons (the average bath size) and divide by 96.8 ssf (ssf per rack). To convert to units of panels per bath replacement for conveyorized processes, multiply by the bath size in gallons and divide by 5.6 ssf/panel.

### **Activity-Based Costing (ABC)**

As discussed previously, ABC is a method of allocating indirect or overhead costs to the products or processes that actually incur those costs. Activity-based costs are determined by developing BOAs for critical tasks. A BOA is a listing of the component activities involved in the performance of a certain task, together with the number of times each component activity is performed. The BOA determines the cost of a task by considering the sequence of actions and the resources utilized while performing that task. In this analysis, the costs of critical tasks determined by a BOA are combined with the number of times a critical task is performed, derived from simulation results to determine the total costs of that activity.

BOAs were developed for the following critical tasks performed within MHC alternatives:

- Chemical transport from storage to the MHC process.
- Tank cleanup.
- Bath setup.
- Bath sampling and analysis.

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- Filter replacement.

These BOAs were developed based on information developed for earlier projects involving similar tasks and on information gathered through site visits and general process knowledge. The following discussion uses the BOA for chemical transport, presented in Table 4.20, as an example of how BOAs were developed and used. Appendix G presents the BOAs for other activities.

Key assumptions were developed to set the limits and to designate the critical activity's characteristics. For chemical transport, the assumptions were:

- Chemical costs are not included in the BOA, but are considered within material costs.
- The portion of labor costs considered are not included within production costs.
- Labor rate used is \$10.22 per hour, consistent with the labor rate for an operator level job.
- Multiple chemicals are required for each bath replacement.
- All chemicals for a bath replacement are transported on one forklift trip.
- Chemicals are purchased in containers larger than the line containers used to move chemicals to the MHC process.
- All chemicals are stored in a central storage location.
- Chemicals are maintained in central storage via inventory tracking and physical monitoring.
- A forklift costs \$580/month or \$0.06/minute, including leasing, maintenance, and fuel.
- Forklifts are utilized to move all chemicals.
- Forklifts are parked in an assigned area when not in use.

Each critical task was broken down into primary and secondary activities. For chemical transport, the six primary activities are: paperwork associated with chemical transfer, moving forklift to chemical storage area, locating chemicals in storage area, preparation of chemicals for transfer, transporting chemicals to MHC process, and transporting chemicals from MHC process to actual bath. The secondary activities for the primary activity of "transport chemicals to MHC process" are: move forklift with chemicals, unload line containers, and park forklift in assigned parking area. For each secondary activity the labor, material, and forklift costs are calculated. The sum of the costs of a set of secondary activities equals the cost of the primary activity. The forklift costs are a function of the time that labor and the forklift are used.

For example, for a chemical transport activity that requires two minutes, the labor cost is \$0.34 (based on a labor rate of \$10.22 per hour) and the forklift cost is \$0.12 (based on \$0.06 per minute). Materials costs are determined for materials other than chemicals and tools required for an activity. The total of \$9.11 in Table 4.20 represents the cost of a single act of transporting chemicals to the MHC line. The same BOAs are used for all MHC technologies because either the activities are similar over all MHC technologies or information is unavailable to distinguish among the technologies. However, individual facilities could modify a BOA to best represent their unique situations. Table 4.21 presents costs to perform each of the critical tasks one time.

**Table 4.20 BOAs for Transportation of Chemicals to MHC Line**

Activities	Time (min)	Resources			Cost (\$/transport)
		Labor <sup>a</sup>	Materials <sup>b</sup>	Forklift <sup>c</sup>	
<b>A. Paperwork and Maintenance</b>					
1. Request for chemicals	2	\$0.34	\$0.10	\$0.00	\$0.44
2. Updating inventory logs	1	\$0.17	\$0.05	\$0.00	\$0.22
3. Safety and environmental record keeping	2	\$0.34	\$0.10	\$0.00	\$0.44
<b>B. Move Forklift to Chemical Storage Area</b>					
1. Move to forklift parking area	2	\$0.34	\$0.00	\$0.12	\$0.46
2. Prepare forklift to move chemicals	5	\$0.85	\$0.00	\$0.30	\$1.15
3. Move to line container storage area	2	\$0.34	\$0.00	\$0.12	\$0.46
4. Prepare forklift to move line container	3	\$0.51	\$0.00	\$0.18	\$0.69
5. Move forklift to chemical storage area	2	\$0.34	\$0.00	\$0.12	\$0.46
<b>C. Locate Chemicals in Storage Area</b>					
1. Move forklift to appropriate areas	1	\$0.17	\$0.00	\$0.06	\$0.23
2. Move chemical containers from storage to staging	2	\$0.34	\$0.00	\$0.12	\$0.46
3. Move containers from staging to storage	2	\$0.34	\$0.00	\$0.12	\$0.46
<b>D. Preparation of Chemicals for Transfer</b>					
1. Open chemical container(s)	1	\$0.17	\$0.05	\$0.00	\$0.22
2. Utilize correct tools to obtain chemicals	3	\$0.51	\$0.05	\$0.00	\$0.56
3. Place obtained chemicals in line container(s)	3	\$0.51	\$0.00	\$0.00	\$0.51
4. Close chemical container(s)	1.5	\$0.09	\$0.00	\$0.00	\$0.09
5. Place line container(s) on forklift	1	\$0.17	\$0.00	\$0.06	\$0.23
<b>E. Transport Chemicals to Line</b>					
1. Move forklift to line	2	\$0.34	\$0.00	\$0.12	\$0.46
2. Unload line container(s) at line	1	\$0.17	\$0.00	\$0.06	\$0.23
3. Move forklift to parking area	2	\$0.34	\$0.00	\$0.12	\$0.46
<b>F. Transport Chemicals from Line to Bath</b>					
1. Move line container(s) to bath	1	\$0.17	\$0.00	\$0.00	\$0.17
2. Clean line container(s)	2	\$0.34	\$0.20	\$0.00	\$0.54
3. Store line container(s) in appropriate area	1	\$0.17	\$0.00	\$0.00	\$0.17
<b>Total Cost per Transport</b>					<b>\$9.11</b>

<sup>a</sup> Labor rate = \$10.22 per hour.<sup>b</sup> Materials do not include chemicals or tools.<sup>c</sup> Forklift operating cost = \$0.06 per minute.

**Table 4.21 Costs of Critical Tasks**

Task	Cost
Transportation of Chemicals	\$9.11
Tank Cleanup	\$67.00
Bath Setup	\$15.10
Sampling and Analysis	\$3.70
Filter Replacement	\$17.50

**Fundamental Principles of Cost Analysis**

Previous studies have defined seven principles of a fundamentally sound cost analysis (DeGamo et al., 1996), listed below. This analysis was designed to strictly adhere to these fundamental principles to increase the validity and credibility of the cost formulation.

**Principle 1. Develop the alternatives to be considered:** Table 4.13 identified the MHC technologies and equipment configurations considered in the cost analysis. Figure 4.13 listed the generic process steps and typical bath sequences for each of these technologies. These process steps and bath sequences are used consistently throughout the CTSA.

**Principle 2. Focus on the difference between expected future outcomes among alternatives:** Costs that are the same among all technologies do not need to be considered as there is no difference among alternatives for these costs. However, all costs that differ should be considered, provided the costs can be reliably estimated. Costs quantified in this analysis are capital costs, material costs, utility costs, wastewater costs, production costs, and maintenance costs. These cost categories were summarized earlier in this section and are discussed in more detail in Section 4.2.3.

Other cost categories are expected to differ in the future outcomes, but cannot be reliably estimated. These include waste treatment and disposal costs and quality costs. These costs were considered qualitatively earlier in this section.

**Principle 3. Use a consistent viewpoint:** The costs to produce a job consisting of 350,000 ssf are estimated for each technology and equipment configuration. Efficient MHC technologies with the ability to produce the 350,000 ssf quicker are rewarded by having the cost rates (i.e., \$/hr, etc.) of certain costs held constant, but the overall cost is calculated over a proportionally shorter time period. For example, if labor rates and the number of workers per day are the same, a process that takes 50 percent less time than the baseline to complete a job will have 50 percent lower labor costs than the baseline.

**Principle 4. Use a common unit of measurement:** Costs are normalized to a common unit of measurement, \$/ssf, to compare the relative costs of technologies.

**Principle 5. Consider all relevant criteria:** A thorough cost analysis requires the consideration of all criteria relevant to the overall costs of the technologies. The costs considered in this analysis were defined earlier in this section and are discussed in more detail in Section 4.2.3.

**Principle 6. Make uncertainty explicit:** Uncertainty is inherent in projecting the future outcomes of the alternatives and should be recognized in the cost analysis. Sensitivity analysis techniques are utilized to evaluate the effects of critical variables on cost.

**Principle 7. Examine the analysis for accuracy:** The cost analysis has been peer reviewed by industry, EPA, and other stakeholders to assess its accuracy and validity.

#### 4.2.2 Simulation Results

Simulation models were run for each of the MHC processes. Three types of simulation outputs were obtained for use in the cost analysis:

- The duration and frequency of bath replacements.
- The production time required for each process.
- Down time incurred in producing 350,000 ssf.

The baseline process is used below as an example to explain the results of the simulation.

Table 4.22 presents the bath replacement simulation outputs. The values in the table represent the actual average time for bath replacement for the baseline process. Reviewing the table reveals that the cleaner/conditioner bath requires replacement nine times. Each replacement takes an average of 133 minutes. The total replacement time represents the total time the process is down due to bath replacements. Summing over all baths, bath replacement consumes 179 hours (10,760 minutes) when using the non-conveyorized electroless copper process to produce 350,000 ssf. Bath replacement simulation outputs for the other MHC processes are presented in Appendix G.

**Table 4.22 Example Simulation Output for Non-Conveyorized Electroless Copper Process: Frequency and Duration of Bath Replacements**

Chemical Bath	Frequency	Avg. Time/Replacement (minutes)	Total Time (minutes)
Cleaner/Conditioner	9	138	1,240
Microetch	18	146	2,630
Predip	8	125	1,000
Catalyst	1	230	230
Accelerator	16	130	2,080
Electroless Copper	10	114	1,140
Acid Dip	6	146	876
Anti-Tarnish	13	120	1,560
<b>Total</b>	<b>81</b>	<b>133</b>	<b>10,760</b>

As shown in the example, the bath replacement output value may be more than or less than the bath replacement input values reported in Tables 4.17 and 4.18. In this case, the input value for non-conveyorized electroless copper processes is 180 minutes, but the output values range from 114 to 230 minutes. Bath maintenance output values are less than input values when,

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on average, the bath is shut down with less than 180 minutes remaining in the shift. Under this scenario, the simulation model assumes that the employee will stay on past the end of the shift to complete the bath replacement. Thus, only the time remaining in a normal 8-hour shift is charged to down time.

Alternately, bath maintenance output values may be greater than input values if more than 180 minutes remain in the shift when the bath is shut down. In this case, the simulation model assumes that all racks or panels will clear the system prior to shutting down the line for a bath replacement. Thus, bath replacement times greater than 180 minutes account for the cycle time required for racks and/or panels to clear the system.

Table 4.23 presents the second and third types of simulation output, the total production time required for each process, and the down time incurred by each process in producing 350,000 ssf. Total production time is the sum of actual operating time and down time. Down time includes the 1.2 hours per day the line is assumed inactive plus the time the process is down for bath replacements. Again, actual simulation outputs are presented in Appendix G.

**Table 4.23 Production Time and Down Time for MHC Processes to Produce 350,000 ssf**

MHC Process	Total Production Time <sup>a</sup>		Total Down Time <sup>a</sup>	
	minutes	days	minutes	days
Electroless Copper, non-conveyorized (BASELINE)	163,500	401	33,900	83.2
Electroless Copper, conveyorized	36,100	88.4	16,300	40.0
Carbon, conveyorized	50,800	125	11,800	28.9
Conductive Polymer, conveyorized	29,100	71.3	7,110	17.4
Graphite, conveyorized	33,400	82.0	6,490	15.9
Non-Formaldehyde Electroless Copper, non-conveyorized	74,600	183	16,400	40.1
Organic-Palladium, non-conveyorized	31,800	77.9	10,800	26.4
Organic-Palladium, conveyorized	45,300	111	18,000	44.1
Tin-Palladium, non-conveyorized	48,500	119	13,600	33.4
Tin Palladium, conveyorized	26,100	63.9	9,010	22.1

<sup>a</sup> To convert from minutes to days, divide by 6.8 hrs per day (408 minutes).

### 4.2.3 Cost Formulation Details and Sample Calculations

This section develops and describes in detail the cost formulation used for evaluating the MHC processes. The overall cost was calculated from individual cost categories that are common to, but expected to vary with, the MHC process alternatives. The cost model was validated by cross-referencing the cost categories with Tellus Institute (White et al., 1992), and Pacific Northwest Pollution Prevention Research Center (Badgett et al., 1995).

The cost model for an MHC alternative is as follows:

$$TC = C + M + U + WW + P + MA$$



where:

TC	=	total cost to produce 350,000 ssf
C	=	capital cost
M	=	material cost
U	=	utility cost
WW	=	wastewater cost
P	=	production cost
MA	=	maintenance cost

The unit cost of producing 350,000 ssf is then represented as follows:

$$\text{Unit Cost (\$/ssf)} = \text{TC (\$)} / 350,000 \text{ ssf}$$

The following sections presents a detailed description of cost calculation methods together with sample calculations for the baseline non-conveyorized electroless copper process. Finally, the results of the sample calculations are summarized and then combined to calculate the total cost and unit cost for the non-conveyorized electroless copper process.

### **Capital Costs**

This section presents methods and sample calculations for calculating capital costs. Capital costs are one-time or periodic costs incurred in the purchase of equipment or facilities. In this analysis, capital costs include the costs of primary equipment, equipment installation, and facility space utilized by the process. Primary equipment is the equipment vital to the operation of the MHC process without which the process would not be able to operate (i.e., bath tanks, heaters, rinse water system, etc.). Installation costs include costs to install the process equipment and prepare it for production. Facility space is the floor space required to operate the MHC process.

Total capital costs for the MHC technologies were calculated as follows:

$$C = (E + I + F) \times \text{UR}$$

where:

E	=	annualized capital cost of equipment (\$/yr)
I	=	annualized capital cost of installation (\$/yr)
F	=	annualized capital cost of facility (\$/yr)
UR	=	utilization ratio, defined as the time in days required to manufacture 350,000 ssf divided by one operating year (250 days)

The UR adjusts annualized costs for the amount of time required to process 350,000 ssf, determined from the simulation models of each process alternative. The components of capital costs are discussed further below followed by sample calculations of capital costs.

**Equipment and Installation Costs.** Primary equipment and installation costs estimates were provided by equipment suppliers and include delivery of equipment and sales tax.

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Equipment estimates were based on basic, no frills equipment capable of processing 100 panels/hr. Equipment estimates did not include auxiliary equipment such as statistical process control or automated sampling equipment sometimes found on MHC process lines.

Annual costs for both the equipment and installation costs were calculated assuming 10-year, straight-line depreciation of equipment and no salvage value. These annual costs were calculated using the following equations:

$$\begin{aligned} E &= \text{equipment cost (\$)} \div 10 \text{ years} \\ I &= \text{installation cost (\$)} \div 10 \text{ years} \end{aligned}$$

**Facility Costs.** Facility costs are capital costs for the floor space required to operate the MHC line. Facility costs were calculated assuming industrial floor space costs \$65/ft<sup>2</sup> and the facility is depreciated over 25 years using straight-line depreciation. The cost per square foot of floor space applies to Class A light manufacturing buildings with basements. This value was obtained from the Marshall Valuation Service (Vishanoff, 1995) and mean square foot costs (Ferguson, 1996). Facility costs were calculated using the following equation:

$$F = [\text{unit cost of facility utilized (\$/ft}^2) \times \text{footprint area/process step (ft}^2/\text{step)} \times \text{number of steps}] \div 25 \text{ years}$$

The “footprint area” is the area of floor space required by MHC equipment, plus a buffer zone to maneuver equipment or have room to work on the MHC process line.<sup>1</sup> The footprint area per process step was calculated by determining the footprint dimensions of each process alternative, adjusting the dimensions for working space, and then determining the area per process step. Because the footprint area depends on the type of process automation, the average dimensions of both conveyORIZED (5 ft x 38 ft) and non-conveyORIZED (6 ft x 45 ft) processes were determined from IPC Workplace Practices Questionnaire data. Since these dimensions account for the equipment footprint only, an additional 8 ft was added to every dimension to allow space for line operation, maintenance, and chemical handling. The floor space required by either equipment type was calculated (1,134 ft<sup>2</sup> for conveyORIZED processes and 1,342 ft<sup>2</sup> for non-conveyORIZED processes) and used to determine the area required per process step. This was done by first identifying the process alternative with the fewest process steps for each automation type, and then dividing the required floor space by that number of steps. This method conservatively estimated the amount of floor space required per process step for conveyORIZED processes at 160 ft<sup>2</sup>/step and for non-conveyORIZED processes at 110 ft<sup>2</sup>/step. The overall area required for each MHC alternative was then calculated using the following equations:

ConveyORIZED:

$$F_C = [\$65/\text{ft}^2 \times 160 \text{ ft}^2/\text{step} \times \text{number of steps per process}] \div 25 \text{ years}$$

Non-conveyORIZED:

$$F_N = [\$65/\text{ft}^2 \times 110 \text{ ft}^2/\text{step} \times \text{number of steps per process}] \div 25 \text{ years}$$

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<sup>1</sup> PWB manufacturers and their suppliers use the term “footprint” to refer to the dimensions of process equipment, such as the dimensions of the MHC process line.

**Sample Capital Costs Calculations.** This section presents sample capital costs calculations for the baseline process. From Figure 4.13, the non-conveyorized electroless copper process consists of 19 chemical bath and rinse steps. Simulation outputs in Table 4.23 indicate this process takes 401 days to manufacture 350,000 ssf of PWB. Equipment vendors estimated equipment and installation costs at \$400,000 and \$70,000, respectively (Microplate, 1996; Coates ASI, 1996; PAL Inc., 1996; Circuit Chemistry, 1996; Western Technology Associates, 1996). The components of capital costs are calculated as follows:

$$\begin{aligned} E &= \$400,000 \div 10 \text{ yrs} = \$40,000/\text{yr} \\ I &= \$70,000 \div 10 \text{ yrs} = \$7,000/\text{yr} \\ F_N &= (\$65/\text{ft}^2 \times 110 \text{ ft}^2/\text{step} \times 19 \text{ steps}) \div 25 \text{ yrs} = \$5,430/\text{yr} \\ UR &= 401 \text{ days} \div 250 \text{ days/yr} = 1.60 \text{ yrs} \end{aligned}$$

Thus, the capital costs for the non-conveyorized electroless copper process to produce 350,000 ssf of PWB are as follows:

$$C = (\$40,000/\text{yr} + \$7,000/\text{yr} + \$5,430/\text{yr}) \times 1.60 \text{ yrs} = \$83,900$$

### **Materials Costs**

Materials costs were calculated for the chemical products consumed in MHC process lines through the initial setup and subsequent replacement of process chemical baths. The following presents equations for calculating materials costs and sample materials cost calculations for the baseline process.

**Materials Cost Calculation Methods.** Chemical suppliers were asked to provide estimates of chemical costs (\$/ssf) early in the project. While some suppliers furnished estimates for one or more of their process alternatives, several suppliers did not provide chemical cost estimates for all of their MHC process lines being evaluated. Still others provided incomplete cost estimates or did not provide any supporting documentation of assumptions used to estimate chemical costs. Therefore, these data could not be used in the comparative cost estimates. Instead, chemical costs were estimated using the methods detailed below.

Chemical baths are typically made-up of one or more separate chemical products mixed together at specific concentrations to form a chemical solution. As PWBs are processed by the MHC line, the chemical baths become contaminated or depleted and require chemical additions on replacement. Baths are typically replaced according to analytical results or by supplier recommended replacement criteria specific to each bath. When the criteria are met or exceeded, the spent bath is removed and a new bath is created. The chemical cost to replace a specific bath one time is the sum of the costs of each chemical product in the bath and is given by the following equation:

$$\text{Chemical cost/bath replacement} = \sum_i [\text{chemical product cost/bath } (\$/\text{gal}) \times \% \text{ chemical product in bath} \times \text{total volume of bath (gal)}]$$

where:

$$i = \text{number of chemical products in a bath}$$

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The University of Tennessee Department of Industrial Engineering contacted suppliers to obtain price quotes in \$/gallon or \$/lb for MHC chemical products. The compositions of the individual process baths were determined from Product Data Sheets for each bath. The average volume of a chemical bath for non-conveyorized processes was calculated to be 75 gallons from IPC Workplace Practices Questionnaire data. For conveyorized processes, however, conveyor speed is constant, thus, the volume of chemicals in a bath varies by bath type to provide the necessary contact time (see Table 4.16 for conveyorized process bath volumes). These data were used in the above equation to calculate the chemical cost per bath replacement for each product line. The bath replacement costs were then averaged across like product lines (i.e., chemical costs from various suppliers of electroless copper processes were averaged by bath type, etc.) to determine an average chemical cost per replacement for each process bath.

To obtain the total materials cost, the chemical cost per bath replacement for each bath was multiplied by the number of bath replacements required (determined by simulation) and then summed over all the baths in an alternative. The cost of chemical additions was not included since no data were available to determine the amount and frequency of chemical additions. Materials costs are given by the following equation:

$$M = \sum_j [\text{chemical cost/bath replacement (\$)} \times \text{number of replacements/bath}]$$

where:

$$j = \text{number of baths in a process}$$

The frequency of replacement for individual process baths was determined using supplier recommended criteria provided on Product Data Sheets and from IPC Workplace Practices Questionnaire data. Simulation models were used to determine the number of times a bath would be replaced while an MHC line processes 350,000 ssf of PWB. Appendix G presents bath replacement criteria used in this analysis and summaries of chemical product cost by supplier and by MHC technology.

**Sample Materials Cost Calculations.** Table 4.24 presents an example of chemical costs per bath replacement for one supplier's electroless copper line. Similar costs are presented in Appendix G for the six electroless copper chemical product lines evaluated. The chemical costs per process bath for all six processes were averaged to determine the average chemical cost per bath for the non-conveyorized electroless copper process.

The chemical cost per bath was then calculated by multiplying the average chemical cost for a bath by the number of bath replacements required to process 350,000 ssf. The costs for each bath were then summed to give the total materials cost for the overall non-conveyorized electroless copper process. Table 4.25 presents the chemical cost per bath replacement, the number of bath replacements required as determined by simulation, the total chemical cost per bath, and the total material cost for the non-conveyorized electroless copper process. Similar material cost calculations for each of the MHC process alternatives are presented in Appendix G.

**Table 4.24 Chemical Cost per Bath Replacement for One Supplier of the Non-Conveyorized Electroless Copper Process**

Bath	Chemical Product	Product Cost <sup>a</sup> (\$)	Percentage of Chemical Product <sup>b</sup>	Chemical Cost/Bath Replacement <sup>c</sup> (\$)
Cleaner/Conditioner	A	\$25.45/gal	6	\$115
Microetch	B	\$2.57/lb	13.8 g/l	\$59
	C	\$7.62/gal	2.5	
	D	\$1.60/gal	18.5	
Predip	E	\$1.31/lb	31.7 g/l	\$22
	F	\$2.00/gal	1.5	
Catalyst	G	\$391.80/gal	4	\$1,186
	H	\$1.31/lb	0.17 g/l	
	I	\$2.00/gal	3.5	
Accelerator	J	\$18.10/gal	20	\$273
Electroless Copper	K	\$27.60/lb	7	\$252
	L	\$16.45/gal	8.5	
	M	\$4.50/gal	0.22	
Neutralizer	N	\$1.60/gal	100	\$120
Anti-Tarnish	O	\$39.00/gal	0.25	\$7

<sup>a</sup> Product cost from supplier of the chemical product.

<sup>b</sup> The percentage of a chemical product in each process bath was determined from Product Data Sheets provided by the supplier of the chemical product.

<sup>c</sup> Cost per bath calculated assuming bath volumes of 75 gallons.

**Table 4.25 Materials Cost for the Non-Conveyorized Electroless Copper Process**

Bath	Chemical Cost/Bath Replacement <sup>a</sup>	Number of Bath Replacements <sup>b</sup>	Total Chemical Cost
Cleaner/Conditioner	\$188	9	\$1,690
Microetch	\$66	18	\$1,190
Predip	\$340	8	\$2,720
Catalyst	\$1,320	1	\$1,320
Accelerator	\$718	16	\$11,500
Electroless Copper	\$317	10	\$3,170
Neutralizer	\$120	6	\$720
Anti-Tarnish	\$16	13	\$208
<b>Total Materials Cost</b>			<b>\$22,500<sup>c</sup></b>

<sup>a</sup> Reported data represents the chemical cost per bath replacement averaged over six electroless copper product lines.

<sup>b</sup> Number of bath replacements required to process 350,000 ssf determined by simulation.

<sup>c</sup> Does not include cost of chemical additions.

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### Utility Costs

Utility costs for the MHC process include water consumed by rinse tanks,<sup>2</sup> electricity used to power the panel transportation system, heaters and other process equipment, and natural gas consumed by drying ovens employed by some MHC alternatives. The utility cost for the MHC process was determined as follows:

$$U = W + E + G$$

where:

- W = cost of water consumed (\$/ssf) to produce 350,000 ssf
- E = cost of electricity consumed (\$/ssf) to produce 350,000 ssf
- G = cost of natural gas consumed (\$/ssf) to produce 350,000 ssf

The following presents utility costs calculation methods and sample utility costs for the baseline process.

**Utility Cost Calculation Methods.** The rate of water consumption depends on both the number of distinct water rinse steps and the flow rate of the water in those steps. The typical number of water rinse steps for each MHC alternative was determined using supplier provided data together with data from the IPC Workplace Practices Questionnaire. Cascaded rinse steps were considered as one rinse step when calculating water consumption since the cascaded rinse steps all utilize the same water. Based on IPC Workplace Practices Questionnaire data, the average water flow rate for individual rinse steps was estimated at 1,185 gals/tank for conveyORIZED processes and 1,840 gals/tank for non-conveyORIZED processes. However, it was assumed that the rinse steps are shut off during periods of process down time. Therefore, daily water consumption rates were adjusted for the percentage of time the process was in operation.

The cost of water was calculated by multiplying the water consumption rate of the MHC process by the production time required to produce 350,000 ssf of PWB, and then applying a unit cost factor to the total. Water consumption rates for MHC alternatives are presented in Section 5.1, Resource Conservation, while production times were determined from the simulation models. A unit cost of \$1.60/1,000 gallons of water was obtained from the *Pollution Prevention and Control Survey* (EPA, 1995a). Following is the equation for calculating water cost:

$$W = \text{quantity of rinse water consumed (gal)} \times \$1.60/1,000 \text{ gal}$$

The rate of electricity consumption for each MHC alternative depends upon the equipment required to operate each alternative. Differences in required process equipment such as the number of heaters, pumps, and type and extent of panel agitation directly affect electricity consumption. The cost of electricity is calculated by multiplying the electricity consumption rate of the MHC process by the production time required to produce 350,000 ssf of PWB, and then applying a unit cost factor to the total. Electricity consumption rates for MHC alternatives are

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<sup>2</sup> Water is also used in MHC chemical baths to dilute chemical products to the appropriate concentration, but this use of water was assumed negligible compared to the water consumed in rinse tanks.

presented in Section 5.2, Energy Impacts, while the required production time was determined by simulation. A unit cost of \$0.0473/kW-hr was obtained from the International Energy Agency. Therefore, the energy cost was calculated using the following equation:

$$E = \text{hourly consumption rate (kW)} \times \text{required production time (hrs)} \times \$0.0473/\text{kW-hr}$$

Natural gas is utilized to fire the drying ovens required by both the graphite and carbon MHC alternatives. The amount of gas consumed was determined by multiplying the natural gas consumption rate for the MHC process by the amount of operating time required by the process to produce 350,000 ssf of PWB and then applying a unit cost to the result. Knoxville Utilities Board (KUB) charges \$0.3683 per therm of natural gas consumed (KUB, 1996a). Thus, the cost of natural gas consumption was calculated by the following equation:

$$G = \text{natural gas consumption rate (therm/hr)} \times \text{required production time (hrs)} \times \$0.3683/\text{therm}$$

The graphite process typically requires a single drying stage while the carbon process requires two drying oven stages. Natural gas consumption rates in cubic feet per hour for both carbon (180 cu.ft./hr) and graphite (90 cu.ft./hr) processes were obtained from Section 5.2, Energy Impacts. The production time required to produce 350,000 ssf of PWB came from simulation results.

**Sample Utility Cost Calculations.** The above methodology was used to calculate the utility costs for each of the MHC alternatives. This section presents sample utility cost calculations for the non-conveyorized electroless copper process.

Simulation results indicate the non-conveyorized electroless copper process is down 83.2 days and takes 401 days overall (at 6.8 hrs/day) to produce 350,000 ssf. It is comprised of seven rinse steps which consume approximately 4.1 million gallons of water during the course of the job (see Section 5.1, Resource Conservation). Electricity is consumed at a rate of 27.2 kW/hr (see Section 5.2, Energy Impacts). The non-conveyorized electroless copper process has no drying ovens and, therefore, does not use natural gas. Based on this information, water, electricity, and gas costs were calculated as follows:

$$\begin{aligned} W &= 4,089,000 \text{ gallons} \times \$1.60/1,000 \text{ gals} = \$6,540 \\ E &= 27.2 \text{ kW} \times (401 \text{ days} - 83.2 \text{ days}) \times 6.8 \text{ hrs/day} \times \$0.0473/\text{kW-hr} = \$2,780 \\ G &= \$0 \end{aligned}$$

Thus, the utility cost for the non-conveyorized electroless copper process was determined by the calculation:

$$U = \$6,540 + \$2,780 + \$0 = \$9,320$$

### Wastewater Costs

**Wastewater Cost Calculation Methods.** Wastewater costs for the MHC processes were only determined for the cost of discharging wastewater to a POTW. The analysis assumes that discharges are made in compliance with local allowable limits for chemical concentrations and other parameters so that no fines are incurred.

Wastewater quantities were assumed equal to the quantity of rinse water used. Rinse water usage was calculated in Section 5.1, Resource Conservation, and used to calculate water costs in the Utility Costs section. The unit costs for fees charged by a POTW for both city and non-city discharges of wastewater were obtained from KUB and averaged for use in calculating wastewater cost (KUB, 1996b). These average unit costs are not flat rates applied to the total wastewater discharge, but rather combine to form a tiered cost scale that applies an incremental unit cost to each level of discharge. The tiered cost scale for wastewater discharges to a POTW is presented in Table 4.26.

**Table 4.26 Tiered Cost Scale for Monthly Wastewater Discharges to a POTW**

Wastewater Discharge Quantity (ccf/month)	City Discharge Cost (\$/ccf/month)	Non-City Discharge Cost (\$/ccf/month)	Average Discharge Cost (\$/ccf/month)
0 - 2	\$6.30	\$7.40	\$6.85
3 - 10	\$2.92	\$3.21	\$3.06
11 - 100	\$2.59	\$2.85	\$2.72
101 - 400	\$2.22	\$2.44	\$2.33
401 - 5,000	\$1.85	\$2.05	\$1.95

Source: KUB, 1996b.

ccf: 100 cubic ft.

The unit costs displayed for each level of discharge are applied incrementally to the quantity of monthly discharge. For example, the first two cubic feet of wastewater discharged in a month are assessed a charge of \$6.85, while the next eight cubic feet cost \$3.06, and so on. The production time required to produce 350,000 ssf of PWB comes from the simulation models. Thus, wastewater costs were calculated as follows:

$$WW = \sum_i [\text{quantity of discharge in tier (ccf/mo)} \times \text{tier cost factor (\$/ccf)}] \times \text{required production time (months)}$$

where:

i = number of cost tiers  
ccf = 100 cubic ft

**Sample Wastewater Cost Calculations.** This section presents sample wastewater calculations for the non-conveyorized electroless copper process. Based on rinse water usage, the total wastewater release was approximately 4.1 million gallons. The required production time in months was calculated using the required production time from Table 4.23 and a 250 day operating year ( $401 \text{ days} \div 250 \text{ days/year} \times 12 \text{ months/yr} = 19.2 \text{ months}$ ). Thus, the monthly



wastewater release was 285 ccf (4,089,000 gallons  $\div$  19.2 months  $\div$  748 gal/hundred cu ft). To calculate the wastewater cost for the non-conveyorized electroless copper process, the tiered cost scale was applied to the quantity of discharge and the resulting costs per tier were summed, as follows:

$$\begin{aligned} \$6.85 \times 2 \text{ ccf/month} &= \$13.70 \text{ ccf/month} \\ \$3.06 \times 8 \text{ ccf/month} &= \$24.48 \text{ ccf/month} \\ \$2.72 \times 90 \text{ ccf/month} &= \$245 \text{ ccf/month} \\ \$2.33 \times 185 \text{ ccf/month} &= \$431 \text{ ccf/month} \end{aligned}$$

$$\text{Monthly discharge cost} = \$13.70 + \$24.48 + \$245 + \$431 = \$714/\text{month}$$

The monthly cost was then multiplied by the number of months required to produce 350,000 ssf of PWB to calculate the overall wastewater treatment cost:

$$\text{WW} = \$714/\text{month} \times 19.2 \text{ month} = \$13,700$$

### **Production Costs**

**Production Cost Calculation Methods.** Production costs for the MHC process include both the cost of labor required to operate the process and the cost of transporting chemicals to the production line from storage. Production costs were calculated by the following equation:

$$P = LA + TR$$

where:

$$\begin{aligned} LA &= \text{production labor cost (\$/ssf) to produce 350,000 ssf} \\ TR &= \text{chemical transportation cost (\$/ssf) to produce 350,000 ssf} \end{aligned}$$

Production labor cost is a function of the number and type of employees and the length of time required to complete a job. The calculation of production labor cost assumes that line operators perform all of the daily activities, excluding bath maintenance, vital to the operation of the MHC process. Labor costs associated with bath maintenance activities, such as sampling and analysis, are presented in the discussion of maintenance costs, below. An average number of line operators was determined for both conveyorized (one line operator) and non-conveyorized (1.1 line operators) processes from IPC Workplace Practices Questionnaire data and supported by site visit observations. Although no significant difference in the number of line operators by automation type was reported in the data, the number of line operators for non-conveyorized processes was adjusted upward to 1.1 to reflect the greater level of labor content for these processes as compared to conveyorized processes.

The labor time required to complete the specified job (350,000 ssf) was calculated assuming an average shift time of eight hours per day and using the number of days required to produce 350,000 ssf of PWB from simulation results. A labor wage of \$10.22/hr was obtained from the American Wages and Salary Survey (Fisher, 1995) and utilized for MHC line operators. Therefore, labor costs for MHC alternatives were calculated as follows:

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$$LA = \text{number of operators} \times \$10.22/\text{hr} \times 8 \text{ hrs/day} \times \text{required production time (days)}$$

The production cost category of chemical transportation cost includes the cost of transporting chemicals from storage to the MHC process line. A BOA, presented in Appendix G, was developed and used to calculate the unit cost per chemical transport. Since chemicals are consumed whenever a bath is replaced, the number of trips required to supply the process line with chemicals equals the number of bath replacements required to produce 350,000 ssf of PWB. Chemical transportation cost was calculated as follows:

$$TR = \text{number of bath replacements} \times \text{unit cost per chemical transport (\$)}$$

**Sample Production Cost Calculations.** For the example of the non-conveyorized electroless copper process, production labor cost was calculated assuming 1.1 operators working for 401 days (see Table 4.23). Chemical transportation cost was calculated based on a cost per chemical transport of \$9.11 (see Table 4.20 and Appendix G) and 81 bath replacements (see Table 4.22). Thus, the production cost was calculated as follows:

$$\begin{aligned} LA &= 1.1 \times \$10.22 \times 8 \text{ hrs/day} \times 401 \text{ days} = \$36,100 \\ TR &= 81 \times \$9.11 = \$737 \end{aligned}$$

thus:

$$P = \$36,100 + \$737 = \$36,800$$

### Maintenance Costs

**Maintenance Costs Calculation Methods.** The maintenance costs for the MHC process include the costs associated with tank cleaning, bath setup, sampling and analysis of bath chemistries, and bath filter replacement. Maintenance costs were calculated as follows:

$$MA = TC + BS + FR + ST$$

where:

$$\begin{aligned} TC &= \text{tank cleanup cost (\$/ssf) to produce 350,000 ssf} \\ BS &= \text{bath setup cost (\$/ssf) to produce 350,000 ssf} \\ FR &= \text{filter replacement cost (\$/ssf) to produce 350,000 ssf} \\ ST &= \text{sampling cost (\$/ssf) to produce 350,000 ssf} \end{aligned}$$

The maintenance costs listed above depend on the unit cost per repetition of the activity and the number of times the activity was performed. For each maintenance cost category, a BOA was developed to characterize the cost of labor, materials, and tools associated with a single repetition of that activity. The BOA and unit cost per repetition for each cost category are presented in Appendix G. It was assumed that the activities and costs characterized on the BOAs are the same regardless of the MHC process or process baths. Unit costs per repetition for both tank cleanup and bath setup were determined to be \$67.00 and \$15.10, respectively.

The number of tank cleanups and bath setups equals the number of bath replacements obtained from process simulation results (see Appendix G). Each time a bath is replaced, the tank is cleaned before a replacement bath is created. The costs of tank cleanup and bath setup are thus given by the following:

$$\begin{aligned} \text{TC} &= \text{number of tank cleanups} \times \$67.00 \\ \text{BS} &= \text{number of bath setups} \times \$15.10 \end{aligned}$$

IPC Workplace Practices Questionnaire data for both filter replacement and bath sampling and analysis were reported in occurrences per year instead of as a function of throughput. Ninetieth percentile values were calculated from these data and used in dermal exposure estimates in Section 3.2, Exposure Assessment. These frequencies were adjusted for this analysis using the URs for the production time required to manufacture 350,000 ssf of PWB. Using the unit costs determined by the BOAs developed for filter replacement (\$17.50 per replacement) and bath sampling and testing (\$3.70 per test), the costs for these maintenance activities were calculated as follows:

$$\begin{aligned} \text{FR} &= \text{annual number of filter replacement} \times \text{UR} \times \$17.50 \\ \text{ST} &= \text{annual number of sampling \& testing} \times \text{UR} \times \$3.70 \end{aligned}$$

The total maintenance cost for each MHC process alternative was determined by first calculating the individual maintenance costs using the above equations and then summing the results.

**Maintenance Costs Sample Calculations.** This section presents sample maintenance costs calculations for the non-conveyorized electroless copper process. From Table 4.23, this process has a production time of 401 days, which gives a UR of 1.60 ( $\text{UR} = 401 \div 250$ ). The number of tank cleanups and bath setups equals the number of bath replacements reported in Table 4.22 (81 bath replacements). As reported in Section 3.2, Exposure Assessment, chemical baths are sampled and tested 720 per year and filters are replaced 100 times per year. Thus, the maintenance costs for the non-conveyorized electroless copper process are:

$$\begin{aligned} \text{TC} &= 81 \times \$67.00 = \$5,430 \\ \text{BS} &= 81 \times \$15.10 = \$1,220 \\ \text{ST} &= 720 \times 1.60 \times \$3.70 = \$4,260 \\ \text{FR} &= 100 \times 1.60 \times \$17.50 = \$2,800 \end{aligned}$$

therefore:

$$\text{MA} = \$5,430 + \$1,220 + \$4,260 + \$2,800 = \$13,700$$

#### **Determination Total Cost and Unit Cost**

The total cost for MHC process alternatives was calculated by summing the totals of the individual costs categories. The unit cost (UC), or cost per ssf of PWB produced, can then be calculated by dividing the total cost by the amount of PWBs produced. Table 4.27 summarizes

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the total cost of manufacturing 350,000 ssf of PWB using the non-conveyorized electroless copper process.

The UC for the non-conveyorized electroless copper process was then calculated as follows:

$$\begin{aligned}\text{UC} &= \text{total cost (TC)} \div 350,000 \text{ ssf} \\ &= \$180,000 \div 350,000 \text{ ssf} \\ &= \$0.51/\text{ssf}\end{aligned}$$

**Table 4.27 Summary of Costs for the Non-Conveyorized Electroless Copper Process**

Cost Category	Component	Component Cost	Totals
Capital Cost	Primary Equipment	\$64,000	
	Installation	\$11,200	
	Facility	\$8,690	<b>\$83,900</b>
Material Cost	Chemical(s)	\$22,500	<b>\$22,500</b>
Utility Cost	Water	\$6,540	
	Electricity	\$2,780	
	Natural Gas	\$0	<b>\$9,320</b>
Wastewater Cost	Wastewater Discharge	\$13,700	<b>\$13,700</b>
Production Cost	Transportation of Material	\$737	
	Labor for Line Operation	\$36,100	<b>\$36,800</b>
Maintenance Cost	Tank Cleanup	\$5,430	
	Bath Setup	\$1,220	
	Sampling and Analysis	\$4,260	
	Filter Replacement	\$2,800	<b>\$13,700</b>
<b>Total Cost</b>			<b>\$180,000</b>

### 4.2.4 Results

Table 4.28 presents the costs for each of the MHC technologies. Table 4.29 presents unit costs (\$/ssf). The total cost of producing 350,000 ssf ranged from a high of \$180,000 for the non-conveyorized electroless copper process to a low of \$33,500 for the conveyorized conductive polymer process. Corresponding unit costs ranged from \$0.51/ssf for the baseline process to \$0.09/ssf for the conveyorized conductive polymer process. With the exception of the non-conveyorized, non-formaldehyde electroless copper process, all of the alternatives cost at least 50 percent less than the baseline. Both conveyorized and non-conveyorized equipment configurations were costed for the electroless copper, tin-palladium, and organic-palladium MHC alternatives. For the electroless copper technology, the conveyorized process was much more economical than the non-conveyorized process. Less difference in unit cost was seen between the tin-palladium technologies (\$0.12/ssf for conveyorized processes and \$0.14/ssf for non-conveyorized processes) and the organic-palladium technologies (\$0.17/ssf for conveyorized processes and \$0.15/ssf for non-conveyorized processes). Non-conveyorized processes are, on average, more expensive (\$0.30) than conveyorized systems (\$0.16).

Total cost data in Table 4.28 illustrate that chemical cost is typically the largest cost (in nine out of ten MHC processes) followed by equipment cost (in one out of ten MHC processes). The high costs of the baseline process appear to be primarily due to the length of time it took this process to produce 350,000 ssf (4,015 days). This is over twice as long as that required by the next process (183 days for non-conveyorized, non-formaldehyde electroless copper).

**Table 4.28 Total Cost of MHC Alternatives**

Cost Category	Cost Components	Electroless Copper, non-conveyorized	Carbon, conveyorized	Conductive Polymer, conveyorized
Capital Cost	Primary Equipment	\$64,000	\$7,470	\$5,560
	Installation	\$11,200	\$299	\$0
	Facility	\$8,690	\$2,690	\$2,250
Material Cost	Chemical(s)	\$22,500	\$32,900	\$10,400
Utility Cost	Water	\$6,540	\$725	\$410
	Electricity	\$2,780	\$836	\$460
	Natural Gas	\$0	\$418	\$0
Wastewater Cost	Wastewater Discharge	\$13,700	\$1,710	\$965
Production Cost	Transportation of Material	\$737	\$446	\$673
	Labor for Normal Production	\$36,100	\$10,200	\$5,830
Maintenance Cost	Tank Cleanup	\$5,430	\$3,280	\$4,960
	Bath Setup	\$1,220	\$740	\$1,120
	Sampling and Testing	\$4,260	\$405	\$436
	Filter Replacement	\$2,800	\$116	\$376
<b>Total Cost</b>		<b>\$180,000</b>	<b>\$62,200</b>	<b>\$33,400</b>

Cost Category	Cost Components	Electroless Copper, conveyorized	Graphite, conveyorized	Non-Formaldehyde Electroless Copper, non-conveyorized
Capital Cost	Primary Equipment	\$6,190	\$3,580	\$29,300
	Installation	\$212	\$131	\$5,120
	Facility	\$2,800	\$1,090	\$3,350
Material Cost	Chemical(s)	\$22,600	\$59,800	\$69,600
Utility Cost	Water	\$642	\$251	\$2,100
	Electricity	\$669	\$462	\$1,310
	Natural Gas	\$0	\$145	\$0
Wastewater Cost	Wastewater Discharge	\$1,450	\$612	\$4,520
Production Cost	Transportation of Material	\$883	\$319	\$682
	Labor for Normal Production	\$7,230	\$6,700	\$16,200
Maintenance Cost	Tank Cleanup	\$6,500	\$2,350	\$5,030
	Bath Setup	\$1,460	\$529	\$1,130
	Sampling and Testing	\$942	\$316	\$691
	Filter Replacement	\$612	\$901	\$214
<b>Total Cost</b>		<b>\$52,200</b>	<b>\$77,200</b>	<b>\$139,200</b>

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**Table 4.28 Total Cost of MHC Alternatives (cont.)**

Cost Category	Cost Components	Organic-Palladium, conveyorized	Organic-Palladium, non-conveyorized
Capital Cost	Primary Equipment	\$5,780	\$4,160
	Installation	\$356	\$256
	Facility	\$2,220	\$1,100
Material Cost	Chemical(s)	\$28,900	\$27,000
Utility Cost	Water	\$635	\$758
	Electricity	\$720	\$325
	Natural Gas	\$0	\$0
Wastewater Cost	Wastewater Discharge	\$1,510	\$1,670
Production Cost	Transportation of Material	\$1,260	\$1,050
	Labor for Normal Production	\$6,530	\$7,190
Maintenance Cost	Tank Cleanup	\$9,250	\$7,710
	Bath Setup	\$2,080	\$1,740
	Sampling and Testing	\$411	\$288
	Filter Replacement	\$271	\$385
<b>Total Cost</b>		<b>\$59,900</b>	<b>\$53,700</b>

Cost Category	Cost Components	Tin-Palladium, conveyorized	Tin-Palladium, non-conveyorized
Capital Cost	Primary Equipment	\$1,280	\$4,760
	Installation	\$205	\$381
	Facility	\$1,490	\$1,910
Material Cost	Chemical(s)	\$25,500	\$22,300
Utility Cost	Water	\$317	\$1,010
	Electricity	\$468	\$635
	Natural Gas	\$0	\$0
Wastewater Cost	Wastewater Discharge	\$754	\$2,340
Production Cost	Transportation of Material	\$537	\$455
	Labor for Normal Production	\$5,230	\$10,700
Maintenance Cost	Tank Cleanup	\$3,950	\$3,350
	Bath Setup	\$891	\$755
	Sampling and Testing	\$493	\$916
	Filter Replacement	\$332	\$616
<b>Total Cost</b>		<b>\$41,400</b>	<b>\$50,100</b>

**Table 4.29 MHC Alternative Unit Costs**

<b>MHC Alternative</b>	<b>Production (ssf/yr)</b>	<b>Total Cost (\$)</b>	<b>Unit Cost (\$/ssf)</b>
Electroless Copper, non-conveyorized (BASELINE)	350,000	\$180,000	\$0.51
Carbon, conveyorized	350,000	\$62,200	\$0.18
Conductive Polymer, conveyorized	350,000	\$33,400	\$0.09
Electroless Copper, conveyorized	350,000	\$52,200	\$0.15
Graphite, conveyorized	350,000	\$77,200	\$0.22
Non-Formaldehyde Electroless Copper, non-conveyorized	350,000	\$139,200	\$0.40
Organic-Palladium, conveyorized	350,000	\$59,900	\$0.17
Organic-Palladium, non-conveyorized	350,000	\$53,700	\$0.15
Tin-Palladium, conveyorized	350,000	\$41,400	\$0.12
Tin-Palladium, non-conveyorized	350,000	\$50,100	\$0.14

#### 4.2.5 Sensitivity Analysis

This section presents the results of sensitivity analyses to determine the effects of critical variables on overall costs. Three separate sensitivity analyses were performed, including sensitivity analyses to determine the following:

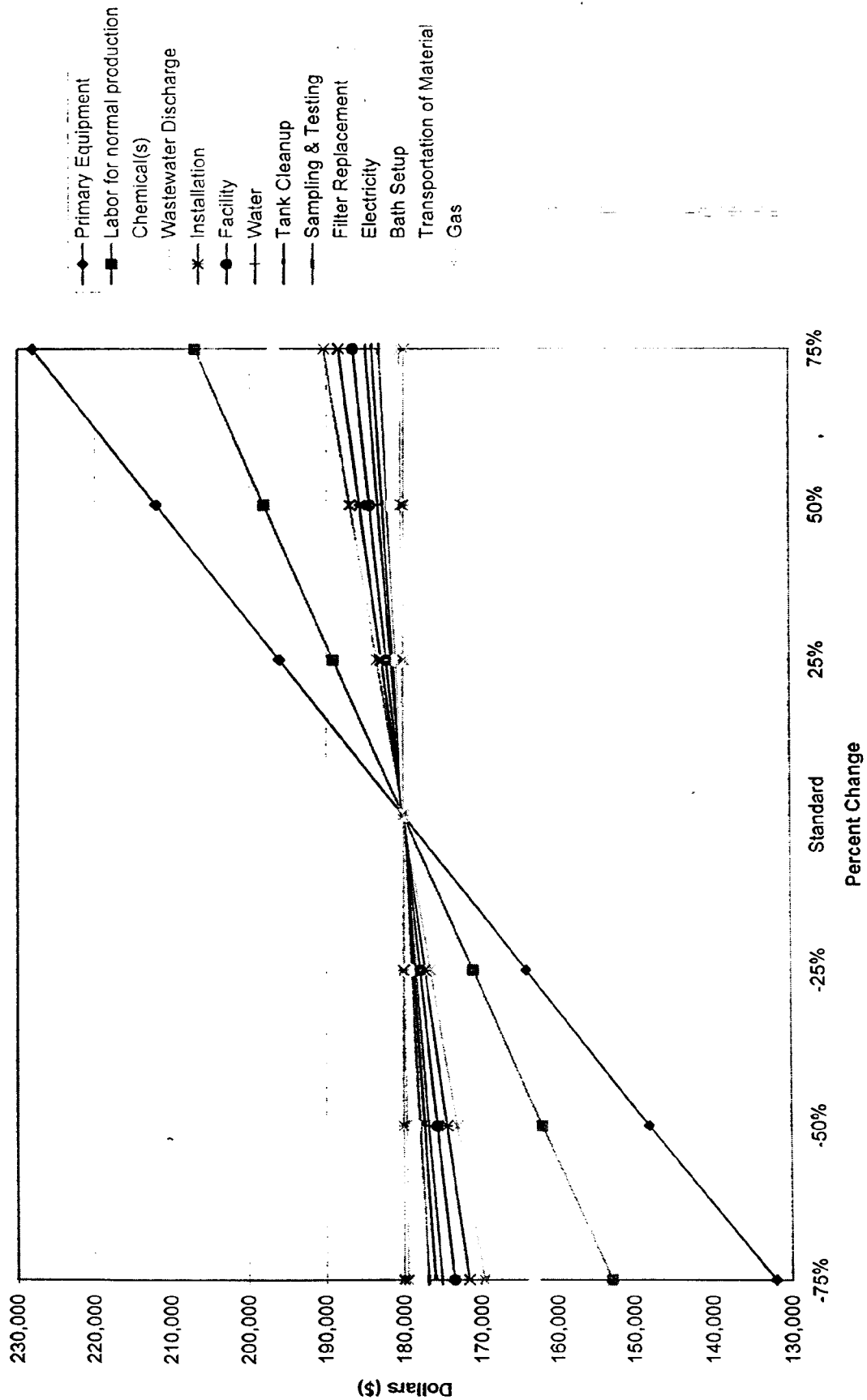
- The effects of the various cost components on the overall cost of the alternatives.
- The effects of down time on the cost of the baseline process.
- The effects of water consumption on the cost of the baseline process.

To determine the effects of the various cost components on overall cost, each cost component was increased and decreased by 25 percent, 50 percent and 75 percent, and an overall cost was calculated. Figure 4.15 presents the results of this sensitivity analysis for the baseline process. Appendix G presents the results of this type of sensitivity analysis for the alternatives. The results indicate two groupings of cost components: 1) those that have little impact on the overall cost; and 2) those which have significant impact on the overall cost of an MHC alternative. The first category includes tank cleanup, electricity, filter replacement, sampling and analysis, bath setup, transportation, and natural gas costs. The second category includes equipment, labor, and chemical costs.

To determine the effects of down time on the overall cost of the baseline process, the duration of bath replacements was reduced by 33 percent and 67 percent. Both the 33 and 67 percent reductions led to a less than one percent reduction in overall cost. These results indicate the effects of down time on overall costs are small.

Water consumption was also reduced by 33 percent and 67 percent to determine its effects on the overall cost of the baseline process. Reducing water consumption affects both water costs and wastewater discharge costs. Reducing water consumption by 33 percent resulted in an overall cost reduction of 2.8 percent, while reducing water consumption by 67 percent reduced the overall cost by 5.9 percent.

Figure 4.15 Sensitivity Analysis for the Non-ConveyORIZED Electroless Copper Process





### 4.2.6 Conclusions

This analysis developed comparative costs for seven MHC technologies, including electroless copper, conductive polymer, carbon, graphite, non-formaldehyde electroless copper, organic-palladium, and tin-palladium processes. Costs were developed for each technology and equipment configuration for which data were available from the IPC Workplace Practices Questionnaire and Performance Demonstration, for a total of ten processes (four non-conveyorized processes and six conveyorized processes). Costs were estimated using a hybrid cost model which combines traditional costs with simulation modeling and activity-based costs. The cost model was designed to determine the total cost of processing a specific amount of PWBs through a fully operational MHC line, in this case 350,000 ssf. The cost model does not estimate start-up costs for a facility switching to an MHC alternative. Total costs were divided by the throughput (350,000 ssf) to determine a unit cost in \$/ssf.

The cost components considered include capital costs (primary equipment, installation, and facility costs), materials costs (limited to chemical costs), utility costs (water, electricity, and natural gas costs), wastewater costs (limited to wastewater discharge cost), production costs (production labor and chemical transport costs), and maintenance costs (tank cleanup, bath setup, sampling and analysis, and filter replacement costs). Other cost components may contribute significantly to overall costs, but were not quantified because they could not be reliably estimated. These include wastewater treatment cost, sludge recycling and disposal cost, other solid waste disposal costs, and quality costs.

Based on the results of this analysis, all of the alternatives are more economical than the non-conveyorized electroless copper process. In general, conveyorized processes cost less than non-conveyorized processes. Costs ranged from \$0.51/ssf for the baseline process to \$0.09/ssf for the conveyorized conductive polymer process. Seven process alternatives cost less than \$0.20/ssf (conveyorized carbon at \$0.18/ssf, conveyorized conductive polymer at \$0.09/ssf, conveyorized electroless copper at \$0.15/ssf, non-conveyorized organic palladium at \$0.15/ssf, conveyorized organic-palladium at \$0.17/ssf, and conveyorized and non-conveyorized tin-palladium at \$0.12/ssf and \$0.14/ssf, respectively). Three processes cost more than \$0.20/ssf (non-conveyorized electroless copper at \$0.51/ssf, non-conveyorized non-formaldehyde electroless copper at \$0.40/ssf, and conveyorized graphite at \$0.22/ssf).

Chemical cost was the single largest component cost for nine of the ten processes. Equipment cost was the largest cost for one process. Three separate sensitivity analyses of the results indicated that chemical cost, production labor cost, and equipment cost have the greatest effect on the overall cost results.

### 4.3 REGULATORY STATUS

This section of the CTSA describes the federal environmental regulations that may affect the chemicals in the MHC technologies. Discharges of these chemicals may be restricted by air, water or solid waste regulations, and releases may be reportable under the federal Toxic Release Inventory (TRI) program. This section discusses pertinent portions of the Clean Water Act (Section 4.3.1), the Safe Drinking Water Act (Section 4.3.2), the Clean Air Act (Section 4.3.3), the Resources Conservation and Recovery Act (Section 4.3.4), the Comprehensive Environmental Response, Compensation and Liability Act (Section 4.3.5), the Superfund Amendments and Reauthorization Act and Emergency Planning and Community Right-to-Know Act (Section 4.3.6), and the Toxic Substances Control Act (Section 4.3.7). In addition, it summarizes pertinent portions of the Occupational Safety and Health Act (Section 4.3.8). Section 4.3.9 summarizes the federal environmental regulations by MHC technology. This information is intended to provide an overview of environmental regulations potentially triggered by MHC chemicals. It is not intended to be used as regulatory guidance.

The primary sources of information for this section were the EPA Register of Lists (EPA, 1996) and the EPA document, *Federal Environmental Regulations Affecting the Electronics Industry* (EPA, 1995b). This is a database of federal regulations applicable to specific chemicals that can be searched by chemical. The latter was prepared by the DfE PWB Project. Of the 62 chemicals used in one or more of the MHC technologies, no regulatory listings were found for 21 chemicals.

#### 4.3.1 Clean Water Act

The Clean Water Act (CWA) is the basic federal law governing water pollution control in the U.S. today. The various MHC processes used by the PWB industry contain a number of chemicals that are regulated under the CWA. Applicable provisions, as related to specific chemicals found in MHC technologies, are presented in Table 4.30; these particular provisions and process-based regulations are discussed in greater detail below.

#### **CWA Hazardous Substances and Reportable Quantities**

The CWA designates hazardous substances under Section 311(b)(2)(a) which, when discharged to navigable waters or adjoining shorelines, present an imminent and substantial danger to the public health or welfare, including fish, shellfish, wildlife, shorelines, and beaches. 40 Code of Federal Regulations (CFR) Part 117 establishes the *Reportable Quantity* (RQ) for each substance listed in 40 CFR Part 116. When an amount equal to or in excess of the RQ is discharged, the facility must provide notice to the federal government of the discharge, following Department of Transportation requirements set forth in 33 CFR Section 153.203. Liability for cleanup can result from such discharges. This requirement does not apply to facilities that discharge the substance under a National Pollutant Discharge Elimination System (NPDES) Permit or a CWA Section 404 dredge and fill permit, or to a Publicly-Owned Treatment Works (POTW), as long as any applicable effluent limitations or pretreatment standards have been met. Table 4.30 lists RQs of hazardous substances under the CWA that may apply to chemicals used in the MHC process.

**Table 4.30 CWA Regulations That May Apply to Chemicals in MHC Technologies**

Chemical	CWA 311 RQ (lbs.)	CWA Priority Pollutant	CWA 307a	CWA 304b
Ammonia	100			✓
Ammonium Chloride	5,000			
Copper (I) Chloride; Copper	10	✓	✓	✓
Copper Sulfate	10	✓	✓	✓
Ethylenediaminetetraacetic Acid (EDTA)	5,000			
Formaldehyde	100			
Formic Acid	5,000			
Hydrochloric Acid	5,000			
Isophorone		✓	✓	✓
Phosphoric Acid	5,000			
Potassium Cyanide	10	✓	✓	
Potassium Hydroxide	1,000			
Silver		✓	✓	✓
Sodium Bisulfate	5,000			
Sodium Cyanide	10	✓	✓	
Sodium Hydroxide	1,000			
Sulfuric Acid	1,000			

Abbreviations and definitions:

CWA - Clean Water Act

CWA 311 - Hazardous Substances

RQ - Reportable Quantities of CWA 311 hazardous substances

CWA 307a - Toxic Pollutants

CWA 304b - Effluent Limitations Guidelines

The NPDES permit program (40 CFR Part 122) contains regulations governing the discharge of pollutants to waters of the U.S. Forty states and one territory are authorized to administer NPDES programs that are at least as stringent as the federal program; EPA administers the program in states that are not authorized to do so. The following discussion covers federal NPDES requirements. Facilities may be required to comply with additional state requirements not covered in this document.

The NPDES program requires permits for the discharge of “pollutants” from any “point source” into “navigable waters” (except those covered by Section 404 dredge and fill permits). CWA defines all of these terms broadly, and a source is required to obtain an NPDES permit if it discharges almost anything other than dredge and fill material directly to surface waters. A source that sends its wastewater to a POTW is not required to obtain an NPDES permit, but may be required to obtain an industrial user permit from the POTW to cover its discharge.

### **CWA Priority Pollutants**

In addition to other NPDES permit application requirements, facilities will need to be aware of *priority pollutants* listed in 40 CFR Part 122, Appendix D; this list of 126 compounds

### **4.3 REGULATORY STATUS**

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was developed by EPA to define a specific list of chemicals to be given priority consideration in the development of effluent limitations. Each applicant for an NPDES permit must provide quantitative data for those priority pollutants which the applicant knows or has reason to believe will be discharged in greater than trace amounts. Each applicant must also indicate whether it knows or has reason to believe it discharges any of the other hazardous substances or non-conventional pollutants listed at 40 CFR Part 122, Appendix D. Quantitative testing is not required for the other hazardous pollutants; however, the applicant must describe why it expects the pollutant to be discharged and provide the results of any quantitative data about its discharge for that pollutant. Quantitative testing is required for the non-conventional pollutants if the applicant expects them to be present in its discharge.

#### **CWA Effluent Limitations Guidelines**

A principal means for attaining water quality objectives under the CWA is the establishment and enforcement of technology-based effluent limitations, which are based on the pollutant control capabilities of available technologies, taking into consideration the economic achievability of these limitations and a number of other factors. Because of differences in production processes, quantities and composition of discharges, separate standards are established for discharges associated with different industry categories. These standards are referred to as technology-based effluent limitation guidelines.

The effluent limitation to be applied to a particular pollutant in a particular case depends on the following:

- Whether the pollutant is conventional, nonconventional, or toxic.
- Whether the point source is a new or existing source.
- Whether the point source discharges directly to the waters of the U.S. or to a POTW. (Facilities that discharge to POTWs must comply with the pretreatment standards.)

Existing sources must comply with either best practicable control technology currently available (BPT), best conventional control technology (BCT), or best available control technology economically practicable (BAT) standards. New facilities must comply with New Source Performance Standards. NPDES permits must also contain any more stringent permit limitations based on state water quality standards.

In the absence of effluent limitation guidelines for a facility category, permit writers establish technology-based controls using their Best Professional Judgement. In essence, the permit writer undertakes an effluent guideline-type analysis for a single facility. The permit writer will use information such as permit limits from similar facilities using similar treatment technology, performance data from actual operating facilities, and scientific literature. Best Professional Judgement may not be used in lieu of existing effluent guidelines. These guidelines apply only to direct dischargers of wastewater.

#### **Pretreatment Standards**

Only those facilities that discharge pollutants into waters of the U.S. need to obtain an NPDES permit. Facilities that discharge to POTWs, however, must comply with pretreatment

requirements, as set out in Section 307 of the CWA. These requirements were developed because of concern that discharger's waste containing toxic, hazardous, or concentrated conventional industrial wastes might "pass through" POTWs or that pollutants might interfere with the successful operation of the POTW.

40 CFR Part 413 contains pretreatment standards for existing sources. Existing sources are those which, since July 15, 1983, have not commenced construction of any building or facility that might result in a discharge. For the MHC step of the PWB manufacturing process, the main pollutant of concern is copper and copper compounds. Table 4.31 describes PWB pretreatment standards applicable to copper.

**Table 4.31 PWB Pretreatment Standards Applicable to Copper**

	Maximum for 1 day (mg/l)	Average Daily Value for 4 Consecutive Days (mg/l)
Facilities discharging 38,000 liters or more per day - Existing Sources	4.5	2.7
Facilities discharging 38,000 liters or more per day - Existing Sources	401 <sup>a</sup>	241 <sup>a</sup>
All plants except job shops and independent PWB manufacturers - Existing Sources (metal finishing) <sup>b</sup>	3.38	2.07
New Sources <sup>c</sup> Limitations (metal finishing)	3.38	2.07

<sup>a</sup> This category reflects mass-based standards for mg/square foot operation, and may be applied in place of the preceding category under prior agreement between a source subject to these standards and the POTW receiving such regulated wastes.

<sup>b</sup> "Metal finishing" applies to plants performing any of the following operations on any basis material: electroplating, electroless plating, anodizing, coating, chemical etching and milling and PWB manufacturing. Pretreatment standards have been promulgated for Total Toxic Organics (TTO) in this category; none of the chemicals evaluated in the MHC technologies are listed.

<sup>c</sup> Pretreatment standards for new sources applies to facilities that commenced construction after July 15, 1983.

### 4.3.2 Safe Drinking Water Act

The Federal Safe Drinking Water Act (SDWA) was first passed in 1974; it has been amended several times. The purpose of the SDWA is to make sure the drinking water supplied to the public is safe and wholesome. It requires water monitoring and limitations on the presence of chemical contaminants, viruses, and other disease-causing organisms in public water systems that serve 25 or more people. The SDWA also includes provisions for protection of groundwater resources in areas around wells that supply public drinking water. In addition, the injection of wastes into deep wells that are above or below drinking water sources are regulated by the SDWA Underground Injection Program (40 CFR Part 144). While most of the regulations under the SDWA affect public water supplies and suppliers, PWB manufacturers could be affected by the groundwater protection policies or the regulation of underground injection wells.

#### **SDWA National Primary and Secondary Drinking Water Regulations**

The SDWA National Primary Drinking Water Regulations (NPDWR) (40 CFR Part 141) set maximum concentrations for substances found in drinking water that may have an adverse

### 4.3 REGULATORY STATUS

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affect on human health. The National Secondary Drinking Water Regulations (NSDWR)(40 CFR Part 143) established guidelines for contaminants in drinking water that primarily affect the aesthetic qualities related to public acceptance of drinking water. The NSDWR are not federally enforceable but are intended as guidelines for the states. Table 4.32 presents MHC chemicals listed by these provisions of the SDWA.

**Table 4.32 SWDA Regulations That May Apply to Chemicals in MHC Technologies**

Chemical	SWDA NPDWR	SWDA NSDWR
Copper (I) Chloride; Copper	✓	✓
Copper Sulfate	✓	✓
Fluoroboric Acid (as fluoride)	✓	✓
Silver		✓

Abbreviations and definitions:

SDWA - Safe Drinking Water Act

SDWA NPDWR - National Primary Drinking Water Rules

SDWA NSDWR - National Secondary Drinking Water Rules

#### 4.3.3 Clean Air Act

The Clean Air Act (CAA), with its 1990 amendments, sets the framework for air pollution control in the U.S. The various MHC technologies produce a number of pollutants that are regulated under the CAA. Applicable provisions, as related to specific chemicals, are presented in Table 4.33; these particular provisions and process-based regulations are discussed below.

#### Hazardous Air Pollutants

Section 112 of the CAA established a program of regulation development for 189 hazardous air pollutants and directed EPA to add other compounds to the list as needed. EPA is authorized to establish Maximum Achievable Control Technology (MACT) standards for source categories that emit at least one of the pollutants on the list. Chemicals listed in Section 112(b) of the CAA that are used in PWB manufacturing are shown in Table 4.33. EPA is in the process of identifying categories of industrial facilities that emit substantial quantities of any of these 189 pollutants and will develop emissions limits for those industry categories.

Section 112(r) of the CAA deals with sudden releases of or accidents involving acutely toxic, explosive, or flammable chemicals. This provision, added by the CAA Amendments of 1990, establishes a list of substances which, if present in a process in a quantity in excess of a threshold, would require that the facility establish a Risk Management Program to prevent chemical accidents. This program would include preparing a risk management plan for submission to the state and to local emergency planning organizations.

**Table 4.33 CAA Regulations That May Apply to Chemicals in MHC Technologies**

Chemical	CAA 111	CAA 112b Hazardous Air Pollutants	CAA 112r
2-Ethoxyethanol	✓	✓	
1,3-Benzenediol	✓		
2-Butoxyethanol Acetate; Butylcellusolve Acetate	✓		
Ammonia			✓
Diethylene Glycol Ethyl Ether	✓		
Diethylene Glycol Methyl Ether	✓	✓	
Dimethylformamide	✓	✓	
Ethylene Glycol	✓	✓	
Fluoroboric Acid (as fluoride)	✓		
Formaldehyde	✓	✓	✓
Formic Acid	✓		
Hydrochloric Acid		✓	✓
Isophorone	✓	✓	
Methanol	✓	✓	
p-Toluene Sulfonic Acid	✓		
Potassium Cyanide		✓	
Sodium Cyanide		✓	
Sulfuric Acid	✓		

Abbreviations and definitions:

CAA - Clean Air Act

CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants-Equipment Leaks Chemical List

CAA 112b - Hazardous Air Pollutant

CAA 112r - Risk Management Program

### **Minimum Standards for State Operating Permit Programs**

The CAA and its implementing regulations (at 40 CFR Part 70) define the minimum standards and procedures required for state operating permit programs. The permit system is a new approach established by the 1990 Amendments that is designed to define each source's requirements and to facilitate enforcement. In addition, permit fees will generate revenue to fund implementation of the program.

Any facility defined as a "major source" is required to secure a permit. Section 70.2 of the regulations defines a source as a single point from which emissions are released or as an entire industrial facility that is under the control of the same person(s). A major source is defined as any source that emits or has the potential to emit:

- Ten tons per year (TPY) or more of any hazardous air pollutant.
- Twenty-five TPY or more of any combination of hazardous air pollutants.
- One hundred TPY of any air pollutant.

For ozone non-attainment areas, major sources are defined as sources with the potential to emit:

### **4.3 REGULATORY STATUS**

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- One hundred TPY or more of volatile organic compounds (VOCs) in areas defined as marginal or moderate.
- Fifty TPY or more of VOCs in areas classified as serious.
- Twenty-five TPY or more of VOCs in areas classified as severe.
- Ten TPY or more of VOCs in areas classified as extreme.

In addition to major sources, all sources that are required to undergo New Source Review are subject to New Source Performance Standards, or are identified by federal or state regulations, must obtain a permit.

By November 15, 1993, each state must submit a design for an operating permit program to EPA for approval. EPA must either approve or disapprove the state's program within one year after submission. Once approved, the state program goes into effect.

Major sources, as well as the other sources identified above, must submit their permit applications to the state within one year of approval of the state program. (This was scheduled to take place near the end of 1995.) Once a source submits an application, it may continue to operate until the permit is issued. Permit issuance may take years because permit processing allows time for terms and conditions to be presented to and reviewed by the public and neighboring states as well as by EPA. Applicants should make certain that their applications contain a comprehensive declaration of all allowable emissions, because current emissions are used as the basis for calculating proposed reductions to meet future limits.

When issued, the permit will include all air requirements applicable to the facility. Among these are compliance schedules, emissions monitoring, emergency provisions, self-reporting responsibilities, and emissions limitations. Five years is the maximum permit term.

As established in 40 CFR Part 70, the states are required to develop fee schedules to ensure the collection and retention of revenues sufficient to cover permit program costs. The CAA sets a presumptive minimum annual fee of \$25 per ton for all regulated pollutants (except carbon monoxide), but states can set higher or lower fees so long as they collect sufficient revenues to cover program costs.

#### **4.3.4 Resource Conservation and Recovery Act**

One purpose of the Resource Conservation and Recovery Act (RCRA) of 1976 (as amended in 1984) is to set up a cradle-to-grave system for tracking and regulating hazardous waste. EPA has issued regulations, found in 40 CFR Parts 260-299, which implement the federal statute. These regulations are Federal requirements. As of March 1994, 46 states have been authorized to implement the RCRA program and may include more stringent requirements in their authorized RCRA programs. In addition, non-RCRA-authorized states (Alaska, Hawaii, Iowa, and Wyoming) may have state laws that set out hazardous waste management requirements. A facility should always check with the state when analyzing which requirements apply to their activities.

To be a hazardous waste, a material must first be a solid waste, which is defined broadly under RCRA and RCRA regulations. Assuming the material is a solid waste, the first evaluation



to be made is whether it is also considered a hazardous waste. 40 CFR Part 261 addresses the identification and listing of hazardous waste. The waste generator has the responsibility for determining whether a waste is hazardous, and what classification, if any, may apply to the waste. The generator must examine the regulations and undertake any tests necessary to determine if the wastes generated are hazardous. Waste generators may also use their own knowledge and familiarity with the waste to determine whether it is hazardous. Generators may be subject to enforcement penalties for improperly determining that a waste is not hazardous.

### **RCRA Hazardous Waste Codes**

Wastes can be classified as hazardous either because they are listed by EPA through regulation in 40 CFR Part 261 or because they exhibit certain characteristics: toxicity, corrosivity, reactivity, or ignitability. Listed hazardous wastes are specifically named (e.g., discarded commercial toluene, spent non-halogenated solvents). Characteristic hazardous wastes are solid waste which “fail” a characteristic test, such as the RCRA test for ignitability.

There are four separate lists of hazardous wastes in 40 CFR Part 261. If any waste from a PWB facility is on any of these lists, the facility is subject to regulation under RCRA. The listing is often defined by industrial processes, but all wastes are listed because they contain particular chemical constituents (these constituents are listed in Appendix VII to Part 261). Section 261.31 lists wastes from non-specific sources and includes wastes generated by industrial processes that may occur in several different industries; the codes for such wastes always begin with the letter “F.” The second category of listed wastes (40 CFR Section 261.32) includes hazardous wastes from specific sources; these wastes have codes that begin with the letter “K.” The remaining lists (40 CFR Section 261.33) cover commercial chemical products that have been or are intended to be discarded; these have two letter designations, “P” and “U.” Waste codes beginning with “P” are considered acutely hazardous, while those beginning with “U” are simply considered hazardous. Listed wastes from chemicals that are used in an MHC process are shown in Table 4.34. While this table is intended to be as comprehensive as possible, individual facilities may use other chemicals and generate other listed hazardous wastes that are not included in Table 4.34. Facilities may wish to consult the lists at 40 CFR 261.31-261.33.<sup>3</sup>

**Table 4.34 RCRA Hazardous Waste Codes That May Apply to Chemical Wastes From MHC Technologies**

Chemical	U Waste Code	P Waste Code
2-Ethoxyethanol	U359	
1,3-Benzenediol	U201	
Formaldehyde	U122	
Formic Acid	U123	
Methanol	U154	
Potassium Cyanide		P098
Sodium Cyanide		P106

<sup>3</sup> Lists of the “F, P, K and U” hazardous wastes can also be obtained by calling the EPA RCRA/Superfund/EPCRA Hotline at (800) 424-9346.

### **Generator Status**

The hazardous waste generator is defined as any person, by site, who creates a hazardous waste or makes a waste subject to RCRA Subtitle C. Generators are divided into three categories:

- Large Quantity Generators (LQG) - These facilities generate at least 1,000 kg (approximately 2,200 lbs) of hazardous waste per month, or greater than 1 kg (2.2 lbs) of acutely hazardous waste per month.
- Small Quantity Generators (SQG) - These facilities generate greater than 100 kg (approximately 220 lbs) but less than 1,000 kg of hazardous waste per month, and up to 1 kg (2.2 lbs) per month of acutely hazardous waste.
- Conditionally Exempt Small Quantity Generators (CESQG) - These facilities generate no more than 100 kg (approximately 220 lbs) per month of hazardous waste and up to 1 kg (2.2 lbs) per month of acutely hazardous waste.

Large and small quantity generators must meet many similar requirements. 40 CFR Part 262 provides that SQGs may accumulate up to 6,000 kg of hazardous waste on-site at any one time for up to 180 days without being regulated as a treatment, storage, or disposal facility (TSDF) and thereby having to apply for a TSDF permit. The provisions of 40 CFR 262.34(f) allow SQGs to store waste on-site for 270 days without having to apply for TSDF status provided the waste must be transported over 200 miles. LQGs have only a 90-day window to ship wastes off-site without needing a RCRA TSDF permit. Keep in mind that most provisions of 40 CFR Parts 264 and 265 (for hazardous waste treatment, storage and disposal facilities) do not apply to generators who send their wastes off-site within the 90- or 180-day window, whichever is applicable.

Hazardous waste generators that do not meet the conditions for CESQGs must (among other requirements such as record keeping and reporting):

- Obtain a generator identification number.
- Store and ship hazardous waste in suitable containers or tanks (for storage only).
- Manifest the waste properly.
- Maintain copies of the manifest, a shipment log covering all hazardous waste shipments, and test records.
- Comply with applicable land disposal restriction requirements.
- Report releases or threats of releases of hazardous waste.

### **Treatment, Storage, or Disposal Facility Status**

As mentioned above, Subtitle C of RCRA (40 CFR Parts 264 and 265) outlines regulation and permit requirements for facilities that treat, store, or dispose of hazardous wastes. Any generator (except some CESQGs [see 40 CFR Part 261.5(g)]), no matter what monthly waste output, who treats, stores, or disposes of waste on site is classified as a TSDF. Every TSDF must comply with 40 CFR Part 264-267 and Part 270, including requirements to apply for a permit and meet certain stringent technical and financial responsibility requirements. Generators who discharge hazardous waste into a POTW or from a point source regulated by an

NPDES permit are not required to comply with TSDF regulations, nor are generators who store waste for short periods (see Generator Status, above).

### 4.3.5 Comprehensive Environmental Response, Compensation and Liability Act

The Comprehensive Environmental Response, Compensation and Liability Act (also known as CERCLA, or more commonly as Superfund) was enacted in 1980. CERCLA is the Act that created the Superfund hazardous substance cleanup program and set up a variety of mechanisms to address risks to public health, welfare, and the environment caused by hazardous substance releases.

#### CERCLA RQs

Substances deemed hazardous under CERCLA are listed in 40 CFR Section 302.4. Under CERCLA, EPA has assigned a reportable quantity (RQ) to most hazardous substances; regulatory RQs are either 1, 10, 100, 1,000, or 5,000 pounds (except for radionuclides). If EPA has not assigned a regulatory RQ to a hazardous substance, its RQ is one pound (Section 102). Any person in charge of a facility (or a vessel) must immediately (within a 24-hour period) notify the National Response Center as soon as a person has knowledge of a release of an amount of a hazardous substance that is equal to or greater than its RQ.<sup>4</sup> There are some exceptions to this requirement, including exceptions for certain continuous releases and for federally permitted releases. Table 4.35 lists RQs of substances under CERCLA that may apply to chemicals used in the MHC process.

**Table 4.35 CERCLA Reportable Quantities That May Apply to Chemicals in MHC Technologies**

Chemical	CERCLA RQ (lbs)	Chemical	CERCLA RQ (lbs)
1,3-Benzenediol	5,000	Isophorone	5,000
Ammonia	100	Methanol	5,000
Ammonia Chloride	5,000	Phosphoric Acid	5,000
Copper (I) Chloride	10	Potassium Cyanide	10
Copper Sulfate	10	Potassium Hydroxide	1,000
Dimethylformamide	100	Silver	1,000
Ethyl Glycol	5,000	Sodium Cyanide	10
Formaldehyde	100	Sodium Hydroxide	1,000
Formic Acid	5,000	Sulfuric Acid	1,000
Hydrochloric Acid	5,000		

Abbreviations and definitions:

CERCLA - Comprehensive Environmental Response, Compensation and Liability Act

CERCLA RQ - CERCLA reportable quantity

<sup>4</sup> The national toll-free number for the National Response Center is (800) 424-8802; in Washington, DC., call (202) 426-2675.

### CERCLA Liability

CERCLA further makes a broad class of parties liable for the costs of removal or remediation of the release or threatened release of any hazardous substance at a facility. Section 107 specifies the parties liable for response costs, including the following: 1) current owners and operators of the facility; 2) owners and operators of facility at the time hazardous substances were disposed; 3) persons who arranged for disposal or treatment, or for transportation for disposal or treatment of such substances; and 4) persons who accepted such substances for transportation for disposal or treatment. These parties are liable for: 1) all costs of removal or remedial action incurred by the federal government, a state, or an Indian tribe not inconsistent with the National Contingency Plan (NCP); 2) any other necessary costs of response incurred by any person consistent with the NCP; 3) damages for injury to natural resources; and 4) costs of health assessments.

#### **4.3.6 Superfund Amendments and Reauthorization Act and Emergency Planning and Community Right-To-Know Act**

CERCLA was amended in 1986 by the Superfund Amendments and Reauthorization Act (SARA). Title III of SARA is also known as the Emergency Planning and Community Right-To-Know Act (EPCRA). Certain sections of SARA and EPCRA may be applicable to MHC chemicals and PWB manufacturers. Table 4.36 lists applicable provisions as related to specific chemicals.

**Table 4.36 SARA and EPCRA Regulations That May Apply to Chemicals in MHC Technologies**

Chemical	SARA 110	EPCRA 302a	EPCRA 313	Chemical	SARA 110	EPCRA 302a	EPCRA 313
2-Ethoxyethanol			✓	Hydrochloric Acid		✓	✓
Ammonia	✓	✓	✓	Hydrogen Peroxide		✓	
Copper (I) Chloride	✓		✓	Isopropyl Alcohol	✓		✓
Copper Sulfate	✓		✓	Methanol			✓
Dimethylformamide			✓	Phosphoric Acid			✓
Ethylene Glycol			✓	Potassium Cyanide		✓	✓
EDTA			✓	Silver	✓		✓
Fluoroboric Acid (as fluoride)	✓			Sodium Cyanide		✓	✓
Formaldehyde	✓	✓	✓	Stannous Chloride (as tin)	✓		
Formic Acid			✓	Sulfuric Acid		✓	✓

Abbreviations and definitions:

SARA - Superfund Amendments and Reauthorization Act

SARA 110 - Superfund Site Priority Contaminant

EPCRA - Emergency Planning & Community Right-To-Know Act

EPCRA 302a - Extremely Hazardous Substances

EPCRA 313 - Toxic Chemical Release Inventory

### **SARA Priority Contaminants**

SARA Section 110 addresses Superfund site priority contaminants. This list contains the 275 highest ranking substances of the approximately 700 prioritized substances. These chemical substances, found at Superfund sites, are prioritized based on their frequency of occurrence, toxicity rating, and potential human exposure. Once a substance has been listed, the Agency for Toxic Substances and Disease Registry (ATSDR) is mandated to develop a toxicological profile that contains general health/hazard assessments with effect levels, potential exposures, uses, regulatory actions, and further research needs.

### **EPCRA Extremely Hazardous Substances**

Section 302(a) of EPCRA regulates extremely hazardous substances and is intended to facilitate emergency planning for response to sudden toxic chemical releases. These chemicals, if present in quantities greater than their threshold planning quantities, must be reported to the State Emergency Response Commission and Local Emergency Planning Committee and addressed in community emergency response plans. These same substances are also subject to regulation under EPCRA Section 304, which requires accidental releases in excess of reportable quantities to be reported to the same state and local authorities.

### **EPCRA Toxic Release Inventory**

Under EPCRA Section 313, a facility in SIC Codes 20-39 that has ten or more full-time employees and that manufactures, processes, or otherwise uses more than 10,000 or 25,000 pounds per year of any toxic chemical listed in 40 CFR Section 372.65 must file a toxic chemical release inventory (TRI) reporting form (EPA Form R) covering releases of these toxic chemicals (including those releases specifically allowed by EPA or state permits) with the EPA and a state agency where the facility is located. Beginning with the 1991 reporting year, such facilities must also report pollution prevention and recycling data for TRI chemicals pursuant to Section 6607 of the Pollution Prevention Act, 42 USC 13106. The threshold for reporting releases is 10,000 or 25,000 pounds, depending on how the chemical is used (40 CFR Section 372.25). Form R is filed annually, covers all toxic releases for the calendar year, and must be filed on or before the first of July of the following year.

#### **4.3.7 Toxic Substances Control Act**

The Toxic Substances Control Act (TSCA)(40 CFR Part 700-799), originally passed in 1976 and subsequently amended, applies to the manufacturers, importers, processors, distributors, users, and disposers of chemical substances or mixtures. Table 4.37 lists TSCA regulations that may be pertinent to the MHC process.

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**Table 4.37 TSCA Regulations That May Apply to Chemicals in MHC Technologies**

Chemical	TSCA 8d HSDR	TSCA 8a MTL	TSCA 8a PAIR	Chemical	TSCA 8d HSDR	TSCA 8a MTL	TSCA 8a PAIR
Benzotriazole	✓			Palladium Chloride			✓
Diethylene Glycol Methyl Ether	✓		✓	Silver			✓
Dimethylformamide	✓		✓	Sodium Cyanide		✓	
Formaldehyde		✓		Triethanolamine		✓	✓
Isophorone	✓		✓	Vanillin		✓	
Isopropyl Alcohol		✓	✓				

Abbreviations and definitions:

TSCA - Toxic Substances Control Act

TSCA 8d HSDR - Health & Safety Data Reporting Rules

TSCA MTL - Master Testing List

TSCA 8a PAIR - Preliminary Assessment Information Rule

### **Testing Requirements**

Section 4 authorizes EPA to require the testing of any chemical substance or mixture on finding that such testing is necessary due to insufficient data from which the chemical's effects can be predicted and that the chemical either may present an unreasonable risk of injury to health or the environment or the chemical is produced in substantial quantities or may result in substantial human exposure.

The TSCA Master Testing List (MTL) is a list compiled by EPA's Existing Chemicals Program to set the Agency's testing agenda under TSCA Section 4. The major purposes are to: 1) identify chemical testing needs; 2) focus limited EPA resources on those chemicals with the highest priority testing needs; 3) identify and publicize EPA's testing priorities for existing chemicals; 4) obtain broad public comments on EPA's testing program and priorities; and 5) encourage initiatives by industry to help EPA meet those priority needs. Since 1990, EPA has: 1) added 222 specific chemicals and nine categories to the MTL; 2) deleted 45 chemicals from the MTL; 3) proposed testing for 113 chemicals via proposed rulemaking under TSCA Section 4; 4) required testing for six chemicals and one category via final TSCA Section 4 test rules, negotiated consent orders, or voluntary testing agreements; and 5) made risk assessment or management decisions on 41 chemicals based on TSCA Section 4 test results received. The MTL now contains over 320 specific chemicals and nine categories.

### **Existing Chemical Requirements**

Section 6 authorizes EPA, to the extent necessary to protect adequately against unreasonable risk using the least burdensome requirements, to prohibit the manufacture, processing, or distribution in commerce of a chemical substance; to limit the amounts, concentrations, or uses of it; to require labeling or record keeping concerning it; or to prohibit or otherwise regulate any manner or method of disposal, on finding there is a reasonable basis to conclude that the chemical presents or will present an unreasonable risk of injury to human health or the environment.

### **Preliminary Assessment Information Rules**

Section 8(a) of TSCA, the Preliminary Assessment Information Rules (PAIR), establishes procedures for chemical manufacturers and processors to report production, use, and exposure-related information on listed chemical substances. Any person (except a “small business”) who imports, manufactures, or processes chemicals identified by EPA by rule must report information on production volume, environmental releases, and/or chemical releases. Small businesses are required to report such information in some circumstances.

#### **4.3.8 Occupational Safety and Health Act**

##### **OSHA Hazard Communication Standard**

The Occupational Safety and Health Administration (OSHA) governs the exposure of workers to chemicals in the workplace. Any facility that is required by OSHA’s Hazard Communication Standard (29 CFR Section 1910.1200) to have Material Safety Data Sheets (MSDSs) for certain hazardous chemicals, and that has such chemicals above certain minimum threshold levels, must provide copies of the MSDSs for these substances or a list of the substances to the State Emergency Response Commission (SERC), the Local Emergency Planning Commission (LEPC), and the local fire department. MSDSs must also be made available to workers. In addition, facilities must annually submit to the SERC, the LEPC, and the fire department a Tier I report indicating the aggregate amount of chemicals (above threshold quantities) at their facilities, classified by hazard category. If any agency that receives a Tier I report requests a Tier II report requiring additional information, facilities must submit this second report to the agency within 30 days of receiving a request for such a report. Tier II reports include an inventory of all chemicals at the facility. Most of the chemicals used in the MHC technologies industry are subject to these MSDS and Tier reporting requirements (40 CFR Part 370).

#### **4.3.9 Summary of Regulations by MHC Technology**

Tables 4.38 through 4.45 provide a summary of regulations that may apply to chemicals in each of the MHC technology categories. Chemicals listed in bold in the tables are used in all of the technology product lines evaluated. For example, formaldehyde is used in all of the electroless copper lines evaluated in this study, but dimethylformamide is only used in one product line. PWB manufacturers should check with their chemical supplier or review their MSDSs to determine which chemicals are present in the products they use.

Chemicals and wastes from the MHC alternatives appear to be subject to fewer overall federal environmental regulations than electroless copper. This suggests that implementing an alternative could potentially improve competitiveness by reducing compliance costs.

## 4.3 REGULATORY STATUS

**Table 4.38 Summary of Regulations That May Apply to Chemicals in the Electroless Copper Technology**

Process Chemical <sup>a</sup>	Chemicals Subject to Applicable Regulation																
	CWA				SDWA		CAA			SARA 110	EPCRA		TSCA			RCRA	Waste
	304b	307a	311	Priority Pollutant	NPDWR	NSDWR	111	112b	112r		302a	313	8d HSDR	MTL	8a PAIR	P	U
Ammonium Chloride			✓														
Benzotriazole						✓						✓					
Boric Acid																	
Copper (I) Chloride <sup>b</sup>	✓	✓	✓	✓	✓	✓				✓		✓					
Copper Sulfate <sup>b</sup>	✓	✓	✓	✓	✓	✓				✓		✓					
Dimethylaminoborane																	
Dimethylformamide				✓		✓	✓	✓				✓	✓		✓		
Ethanolamine																	
2-Ethoxyethanol							✓	✓				✓				359	
Ethylenediaminetetraacetic Acid (EDTA)			✓														
Ethylene Glycol				✓			✓	✓				✓					
Fluoroboric Acid (as fluoride)	✓				✓	✓	✓			✓							
Formaldehyde			✓				✓	✓	✓	✓	✓	✓		✓		122	
Formic Acid			✓	✓			✓					✓				123	
Hydrochloric Acid <sup>c</sup>			✓					✓	✓		✓	✓					
Hydrogen Peroxide											✓						
Hydroxyacetic Acid																	
Isopropyl Alcohol, 2- Propanol										✓		✓		✓	✓		
m-Nitrobenzene Sulfonic Acid																	
Magnesium Carbonate																	



## 4.3 REGULATORY STATUS

Process Chemical <sup>a</sup>	Chemicals Subject to Applicable Regulation																
	CWA				SDWA		CAA			SARA 110	EPCRA		TSCA			RCRAWaste	
	304b	307a	311	Priority Pollutant	NPDWR	NSDWR	111	112b	112r		302a	313	8d HSDR	MTL	8a PAIR	P	U
Methanol				✓			✓	✓				✓					154
Palladium																	
Peroxymonosulfuric Acid																	
Potassium Bisulfate																	
Potassium Cyanide		✓	✓	✓	✓			✓			✓	✓				098	
Potassium Hydroxide			✓														
Potassium Persulfate																	
Potassium Sodium Tartrate																	
Potassium Sulfate																	
Sodium Bisulfate			✓														
Sodium Carbonate																	
Sodium Chlorite																	
Sodium Cyanide		✓	✓	✓				✓			✓	✓		✓		106	
Sodium Hydroxide			✓														
Sodium Hypophosphite																	
Sodium Sulfate																	
Stannous Chloride	✓									✓							
Sulfuric Acid			✓				✓				✓	✓					
Tartaric Acid																	
p-Toluene Sulfonic Acid																	
Triethanolamine														✓	✓		

<sup>a</sup> Chemicals in bold were in all electroless copper technologies evaluated, unless otherwise noted.

<sup>b</sup> Either copper (I) chloride or copper sulfate was in all electroless copper lines evaluated.

<sup>c</sup> Hydrochloric acid was listed on the MSDSs for five of six electroless copper lines.

## 4.3 REGULATORY STATUS

**Table 4.39 Summary of Regulations That May Apply to Chemicals in the Carbon Technology**

Process Chemical <sup>a</sup>	Chemicals Subject to Applicable Regulation																
	CWA				SDWA		CAA			SARA 110	EPCRA		TSCA			RCRA Waste	
	304b	307a	311	Priority Pollutant	NPDWR	NSDWR	111	112b	112r		302a	313	8d HSDR	MTL	8a PAIR	P	U
Carbon Black																	
Copper Sulfate	✓	✓	✓	✓	✓	✓				✓		✓					
Ethanolamine																	
Ethylene Glycol				✓			✓	✓				✓					
Potassium Carbonate																	
Potassium Hydroxide			✓														
Sodium Persulfate																	
Sulfuric Acid			✓				✓			✓		✓					

<sup>a</sup> Only one carbon technology was evaluated. All chemicals listed were present in that product line.

## 4.3 REGULATORY STATUS

**Table 4.40 Summary of Regulations That May Apply to Chemicals in the Conductive Ink Technology**

Process Chemical <sup>a</sup>	Chemicals Subject to Applicable Regulation																
	CWA				SDWA		CAA			SARA	EPCRA		TSCA			RCRA Waste	
	304b	307a	311	Priority Pollutant	NPDWR	NSDWR	111	112b	112r	110	302a	313	8d HSDR	MTL	8a PAIR	P	U
2-Butoxyethanol Acetate							✓										
Carbon Black																	
Diethylene Glycol n-Butyl Ether																	
Diethylene Glycol Ethyl Ether							✓										
Diethylene Glycol Methyl Ether							✓	✓					✓		✓		
Graphite																	
Isophorone	✓	✓		✓			✓	✓					✓		✓		
Methanol							✓	✓				✓					154
Silver	✓	✓		✓		✓				✓		✓			✓		

<sup>a</sup> Only one conductive ink technology was evaluated. All chemicals listed were present in that product line.

## 4.3 REGULATORY STATUS

**Table 4.41 Summary of Regulations That May Apply to Chemicals in the Conductive Polymer Technology**

Process Chemical <sup>a</sup>	Chemicals Subject to Applicable Regulation																
	CWA				SDWA		CAA			SARA 110	EPCRA		TSCA			RCRA Waste	
	304b	307a	311	Priority Pollutant	NPDWR	NSDWR	111	112b	112r		302a	313	8d HSDR	MTL	8a PAIR	P	U
1H-Pyrrole																	
Peroxymonosulfuric Acid																	
Phosphoric Acid			✓								✓						
Sodium Carbonate																	
Sodium Hydroxide			✓														
Sulfuric Acid			✓				✓				✓	✓					

<sup>a</sup> Only one conductive polymer technology was evaluated. All chemicals listed were present in that product line.

Table 4.42 Summary of Regulations That May Apply to Chemicals in the Graphite Technology

Process Chemical <sup>a</sup>	Chemicals Subject to Applicable Regulation																
	CWA				SDWA		CAA			SARA	EPCRA		TSCA			RCRA Waste	
	304b	307a	311	Priority Pollutant	NPDWR	NSDWR	111	112b	112r	110	302a	313	8d HSDR	MTL	8a PAIR	P	U
Ammonia	✓		✓						✓	✓	✓	✓					
Copper Sulfate	✓	✓	✓	✓	✓	✓				✓		✓					
Ethanolamine																	
Graphite																	
Peroxymonosulfuric Acid																	
Potassium Carbonate																	
Sodium Persulfate																	
Sulfuric Acid			✓				✓				✓	✓					

<sup>a</sup> Chemicals in bold were in both graphite technologies evaluated.

## 4.3 REGULATORY STATUS

**Table 4.43 Summary of Regulations That May Apply to Chemicals in the Non-Formaldehyde Electroless Copper Technology**

Process Chemical <sup>a</sup>	Chemicals Subject to Applicable Regulation															
	CWA				SDWA		CAA			SARA 110	EPCRA		TSCA			RCRA Waste
	304b	307a	311	Priority Pollutant	NPDWR	NSDWR	111	112b	112r		302a	313	8d HSDR	MTL	8a PAIR	P U
Copper Sulfate	✓	✓	✓	✓	✓	✓				✓		✓				
Hydrochloric Acid			✓					✓	✓		✓	✓				
Hydrogen Peroxide											✓					
Isopropyl Alcohol (2-propanol)										✓		✓		✓	✓	
Potassium Hydroxide			✓													
Potassium Persulfate																
Sodium Chlorite																
Sodium Hydroxide			✓													
Stannous Chloride										✓						
Sulfuric Acid			✓				✓				✓	✓				

<sup>a</sup> Only one non-formaldehyde electroless copper technology was evaluated. All chemicals listed were present in that product line.

Table 4.44 Summary of Regulations That May Apply to Chemicals in the Organic-Palladium Technology

Process Chemical <sup>a</sup>	Chemicals Subject to Applicable Regulation																
	CWA				SDWA		CAA			SARA 110	EPCRA		TSCA			RCRA Waste	
	304b	307a	311	Priority Pollutant	NPDWR	NSDWR	111	112b	112r		302a	313	8d HSDR	MTL	8a PAIR	P	U
Hydrochloric Acid			✓					✓	✓		✓	✓					
Sodium Bisulfate			✓														
Sodium Carbonate																	
Sodium Bicarbonate																	
Sodium Hypophosphite																	
Sodium Persulfate																	
Trisodium Citrate 5,5-Hydrate or Sodium Citrate																	

<sup>a</sup> Only one organic-palladium technology was evaluated. All chemicals listed were present in that product line.

### 4.3 REGULATORY STATUS

**Table 4.45 Summary of Regulations That May Apply to Chemicals in the Tin-Palladium Technology**

Process Chemical <sup>a</sup>	Chemicals Subject to Applicable Regulation															
	CWA				SDWA		CAA			SARA	EPCRA		TSCA			RCRA Waste
	304b	307a	311	Priority Pollutant	NPDWR	NSDWR	111	112b	112r	110	302a	313	8d HSDR	MTL	8a PAIR	P U
1,3-Benzenediol							✓									201
<b>Copper (I) Chloride<sup>b</sup></b>	✓	✓	✓	✓	✓	✓				✓		✓				
<b>Copper Sulfate<sup>b</sup></b>	✓	✓	✓	✓	✓	✓				✓		✓				
Dimethylaminoborane																
Ethanolamine																
Fluoroboric Acid (as fluoride)					✓	✓	✓			✓						
<b>Hydrochloric Acid<sup>c</sup></b>			✓					✓	✓		✓	✓				
Hydrogen Peroxide											✓					
Isopropyl Alcohol (2-propanol)										✓		✓		✓	✓	
Lithium Hydroxide																
<b>Palladium<sup>d</sup></b>																
<b>Palladium Chloride<sup>d</sup></b>															✓	
Phosphoric Acid			✓									✓				
Potassium Carbonate																
Sodium Bisulfate			✓													
Sodium Chloride																
Sodium Hydroxide			✓													
Sodium Persulfate																
<b>Stannous Chloride<sup>e</sup></b>										✓						
<b>Sulfuric Acid<sup>c</sup></b>			✓				✓				✓	✓				
Triethanolamine														✓	✓	
Vanillin														✓		

<sup>a</sup> Chemicals in bold were in all tin-palladium technologies evaluated, unless otherwise noted.

<sup>b</sup> Either copper (I) chloride or copper sulfate was listed on the MSDSs for four of five tin-palladium lines evaluated.

<sup>c</sup> Hydrochloric and sulfuric acid were listed on the MSDSs for four of five tin-palladium lines evaluated.

<sup>d</sup> Palladium or palladium chloride was listed on the MSDS for three of five tin-palladium lines evaluated. The MSDSs for the two other lines did not list a source of palladium.

<sup>e</sup> Stannous chloride was listed on the MSDSs for four of the five tin-palladium lines evaluated. The MSDSs for the remaining tin-palladium product line did not list a source of tin or palladium.



## 4.4 INTERNATIONAL INFORMATION

Several alternatives to the electroless copper process are being adopted more quickly abroad than in the U.S. This section discusses the world market for PWBs and the international use of MHC alternatives. It also discusses factors driving the international use of MHC alternatives, including economic, environmental and regulatory considerations.

### 4.4.1 World Market for PWBs

The total world market for PWBs is approximately \$21 billion (EPA, 1995c). The U.S. and Japan are the leading suppliers of PWBs but Hong Kong, Singapore, Taiwan, and Korea are increasing their market share. In 1994 the U.S. provided 26 percent of the PWBs in the world market, Japan 28 percent, and Europe 18 percent (EPA, 1995c). IPC estimates that domestic PWB imports are approximately \$500 to \$600 million annually (EPA, 1995c). Taiwan comprises approximately 30 to 35 percent of the import market with Japan, Hong Kong, Korea, and Thailand comprising 10 percent each. Domestic PWB exports were approximately \$100 million in 1993, which represents two to three percent of total domestic production (EPA, 1995c).

### 4.4.2 International Use of MHC Alternatives

The alternatives to the traditional electroless copper MHC process are in use in many countries abroad, including England, Italy, France, Spain, Germany, Switzerland, Sweden, Japan, China, Hong Kong, Singapore, Taiwan, and Canada. In addition, most of the suppliers of these alternatives have manufacturing facilities located in the countries to which they sell. One company provides its palladium alternative to Japan, France, Sweden, the UK, Canada, and Germany (Harnden, 1996). Another company, which provides a palladium alternative to electroless copper, provides both processes to England, Italy, France, Spain, Germany, Switzerland, China, Hong Kong, Singapore, and Taiwan. Presently, that company's electroless copper process is used more frequently than the palladium alternative (Nargi-Toth, 1996). However, restrictions on EDTA in Germany are making the use of the palladium alternative almost equal to the use of the traditional electroless copper process. Similarly, in Taiwan and China the use of the palladium process is increasing relative to the electroless copper process due to the high cost of water (Nargi-Toth, 1996). Internationally, one company reports its conductive polymer and organic-palladium processes make up approximately five percent of the world market (Boyle, 1996).

Another company provides its graphite alternative in Germany, England, France, Japan, Taiwan and Hong Kong, and is opening manufacturing facilities in both China and Malaysia within a few months (Carano, 1996). The company's graphite process is reportedly used more frequently in Europe than is its electroless copper process. However, in Asia, the electroless copper process is used more frequently (Carano, 1996).

Several suppliers have indicated that the use of their particular MHC alternative to electroless copper is increasing throughout the international arena. Some suppliers have indicated that the international usage of the electroless copper process is also on the rise but that the MHC alternatives are increasing in usage more rapidly than traditional electroless copper

#### **4.4 INTERNATIONAL INFORMATION**

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processes (Carano, 1996). A pollution prevention and control survey performed under the DfE PWB Project confirmed that the electroless copper is the predominate method employed in the U.S. The survey was conducted of 400 PWB manufacturers in the U.S.; 40 responses were received, representing approximately 17 percent of the total U.S. PWB production (EPA, 1995d). Eighty-six percent of survey respondents use the electroless copper for most of their products, 14 percent use palladium alternatives, and one respondent uses a graphite system (EPA, 1995d). The Pollution Prevention and Control Survey is discussed further in Chapter 1 of the CTSA.

#### **Reasons for Use of Particular Alternatives Internationally**

For the most part, the alternatives to the electroless copper process appear to be employed due to reasons other than environmental pressures. According to international manufacturers who participated in the Performance Demonstration Project, the most common reason for use of an alternative is economics. According to suppliers, some of the alternatives are in fact less costly than the traditional electroless copper process (see Section 4.2 for an analysis of the comparative costs of alternatives developed for the CTSA). An example of this is one company's graphite process, which reportedly costs less than the company's comparable electroless copper process (Carano, 1996). Furthermore, several of the performance demonstration participants in Europe indicated that their use of an alternative MHC process has resulted in increased throughput and decreased manpower requirements.

Some of the economic drivers for adopting alternatives to the electroless copper process internationally also relate to environmental issues. Several of the countries adopting the MHC alternatives have high population densities as compared to the U.S., making water a scarcer resource. As a result, these companies face high costs to buy and treat their wastewater. In Germany, for example, companies pay one cent per gallon to have water enter the plant and then must pay 1.2 cents per gallon to dispose of wastewater (Obermann, 1996). As a result, any alternative that offers a reduction in the use of wastewater is potentially more attractive from a cost-effectiveness standpoint. Several MHC alternatives allow wastewater to be reused a number of times, something that is not available when using the electroless copper process due to the high levels of chelators and copper that cannot be removed from the water except through chemical treatment (Obermann, 1996). Therefore, the costs of buying the water and paying to have it treated are reduced through the use of less water-intensive alternatives.

In some countries there are "pressures" rather than environmental regulations that have led to the adoption of an alternative to the electroless copper MHC process. Some countries have identified the use of EDTA and formaldehyde as areas of potential concern. For instance, in Germany there are restrictions on the use of the chelator EDTA that are making the adoption of non-EDTA using alternatives more attractive (Nargi-Toth, 1996). Some alternatives do not use formaldehyde and as such are used with more frequency than the electroless copper process in countries that are attempting to limit the use of formaldehyde (Harnden, 1996).

#### **Barriers to Trade and Supply Information**

The alternatives to the electroless copper process do not suffer from any readily apparent barriers to trade or tariff restrictions that would make their increased adoption more costly. The alternatives discussed above are all made from readily available materials. Therefore, if the

demand for these alternatives should increase there should be no problem with meeting the increased demand. Most of the suppliers of these alternatives have manufacturing facilities located in the countries to which they sell and so they face no tariffs from importing these chemicals. The companies that wish to use the particular alternative simply contact the manufacturer in their country to purchase the alternatives. Therefore, there are no trade barriers in the form of tariffs making one alternative more attractive to a potential purchaser (Carano, 1996; Nargi-Toth, 1996; Harnden, 1996). As was indicated above, most alternatives are available in the same countries so they all appear to be on equal footing in terms of availability and susceptibility to trade barriers.

#### **4.4.3 Regulatory Framework**

Most of the driving forces leading to the use of an alternative to electroless copper are related to the cost-effectiveness of the alternative. However, there are several regulatory mechanisms in place internationally that favor alternatives to traditional electroless copper processes. These include wastewater effluent requirements and water consumption issues, discussed below.

##### **Wastewater Effluent Requirements**

Suppliers and international performance demonstration participants report that economics, not chemical bans or restrictions on specific chemicals, are the leading cause for the adoption of an MHC alternative. However, wastewater effluent requirements for certain chemicals found in electroless copper processes are also speeding the adoption of other MHC processes. For example, in Germany the chemical EDTA is restricted so that it must be removed from wastewater before the wastewater is discharged to an off-site wastewater treatment facility. This restriction led one manufacturer to replace his electroless copper process with an organic-palladium process (Schwansee, 1996). This restriction is a national one so that all companies must adhere to it.

Also in Germany, the wastewater leaving a plant cannot contain copper in amounts in excess of 0.5 mg/L or any ammonia (Obermann, 1996). The German regulation on copper discharges is much more stringent than comparable regulations in the U.S., where facilities must at least comply with federal effluent regulations and are sometimes subjected to more stringent regulations from the states (EPA, 1995d). The federal effluent guidelines for copper discharges are 3.38 mg/l maximum and 2.07 mg/l average monthly concentration (EPA, 1995d). According to the Pollution Prevention and Control Survey discussed previously, 63 percent of the respondents must meet discharge limitations that are more stringent than the federal effluent limitations (EPA, 1995d). However, only 15 percent of the respondents had to meet effluent limitations that were as stringent as, or more stringent than, the German regulation (EPA, 1995d).

##### **Water Consumption**

As indicated above, water usage is a main concern in many of the international arenas that use these alternatives. While there are few direct regulations on the amount of water that can be used in a MHC process, the cost of buying and treating the water make a more water-intensive process less economical. In Germany, the high cost of purchasing water and discharging

wastewater greatly influences the decision of whether or not to use an alternative. The less water a process uses, the more likely it is that process will be used. In addition, in certain parts of Germany, local authorities examine plans for the MHC process and issue permits to allow use of the line. If the process that is proposed for use is too water-intensive, a permit will not be issued by the local authorities (Carano, 1996). In addition, local authorities sometimes give specific time limits in which an older more water-intensive process must be phased out (Carano, 1996). For example, one international participant in the Performance Demonstration Project uses an older electroless copper process for some of its products. The local authorities have given the company four years to cease operation of the line because it uses too much water (Obermann, 1996).

##### **4.4.4 Conclusions**

The information set forth above indicates that the cost-effectiveness of an alternative has been the main driver causing PWB manufacturers abroad to switch from an electroless copper process to one of the newer alternatives. In addition to the increased capacity and decreased labor requirements of some of the MHC alternatives over the non-conveyorized electroless copper process, environmental concerns also affected the process choice. For instance, the rate at which an alternative consumes water and the presence or absence of strictly regulated chemicals are two factors which have a substantial affect on the cost-effectiveness of MHC alternatives abroad. Finally, in some parts of Germany, local authorities can deny a permit for a new MHC process line if it is deemed too water-intensive, or require an existing MHC process to be replaced. While environmental regulations do not seem to be the primary forces leading toward the adoption of the newer alternatives, it appears that the companies that supply these alternatives are taking environmental regulations and concerns into consideration when designing alternatives to the electroless copper process.

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